MAY 2 0 1988

Y3.N88:2/5016

NUREG/CR-5016
PNL-6341
CSNI No. 140

Compendium and Comparison of International Practice for Plugging, Repair and Inspection of Steam Generator Tubing

Prepared by R. A. Clark, R. J. Kurtz

Pacific Northwest Laboratory
Operated by
Battelle Memorial Institute

Prepared for
U.S. Nuclear Regulatory Commission

Organization for Economic Co-operation and Development

COMPLETED

ORIGINAL

BEST COPY AVAILABLE

NOTICE

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, or any of their employees, makes any warranty, expressed or implied, or assumes any legal liability of responsibility for any third party's use, or the results of such use, of any information, apparatus, product or process disclosed in this report, or represents that its use by such third party would not infringe privately owned rights.

NOTICE

Availability of Reference Materials Cited in NRC Publications

Most documents cited in NRC publications will be available from one of the following sources:

1. The NRC Public Document Room, 1717 H Street, N.W.
   Washington, DC 20555
2. The Superintendent of Documents, U.S. Government Printing Office, Post Office Box 37082
   Washington, DC 20013-7082
3. The National Technical Information Service, Springfield, VA 22161

Although the listing that follows represents the majority of documents cited in NRC publications, it is not intended to be exhaustive.

Referenced documents available for inspection and copying for a fee from the NRC Public Document Room include NRC correspondence and internal NRC memoranda; NRC Office of Inspection and Enforcement bulletins, circulars, information notices, inspection and investigation notices; Licensee Event Reports; vendor reports and correspondence; Commission papers; and applicant and licensee documents and correspondence.

The following documents in the NUREG series are available for purchase from the GPO Sales Program: formal NRC staff and contractor reports, NRC-sponsored conference proceedings, and NRC booklets and brochures. Also available are Regulatory Guides, NRC regulations in the *Code of Federal Regulations*, and *Nuclear Regulatory Commission Issuances*.

Documents available from the National Technical Information Service include NUREG-series reports and technical reports prepared by other federal agencies and reports prepared by the Atomic Energy Commission, forerunner agency to the Nuclear Regulatory Commission.

Documents available from public and special technical libraries include all open literature items, such as books, journal and periodical articles, and transactions. *Federal Register* notices, federal and state legislation, and congressional reports can usually be obtained from these libraries.

Documents such as theses, dissertations, foreign reports and translations, and non-NRC conference proceedings are available for purchase from the organization sponsoring the publication cited.

Single copies of NRC draft reports are available free, to the extent of supply, upon written request to the Division of Information Support Services, Distribution Section, U.S. Nuclear Regulatory Commission, Washington, DC 20555.

Copies of industry codes and standards used in a substantive manner in the NRC regulatory process are maintained at the NRC Library, 7920 Norfolk Avenue, Bethesda, Maryland, and are available there for reference use by the public. Codes and standards are usually copyrighted and may be purchased from the originating organization or, if they are American National Standards, from the American National Standards Institute, 1430 Broadway, New York, NY 10018.

BEST COPY AVAILABLE

NUREG/CR-5016
PNL-6341
CSNI No. 140
R5

Compendium and Comparison of International Practice for Plugging, Repair and Inspection of Steam Generator Tubing

Manuscript Completed: October 1987
Date Published: April 1988

Prepared by
R. A. Clark, R. J. Kurtz

Pacific Northwest Laboratory
Richland, WA 99352

Prepared for
Division of Engineering
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555
NRC FIN B2097

Organization for Economic Co-operation and Development
Nuclear Energy Agency

PREFACE

The Committee on the Safety of Nuclear Installations (CSNI) of the Organization for Economic Cooperation and Development - Nuclear Energy Agency (OECD-NEA) is an international body of scientists and engineers with responsibilities for nuclear safety research and nuclear licensing. The CSNI fosters international cooperation in nuclear safety amongst OECD member countries. In July 1986, the Committee's Principal Working Group on Primary Circuit Integrity agreed it would be useful to those setting criteria and making decisions about plugging of degraded steam generator tubes to have a better appreciation of the criteria presently employed in other member countries and their technical bases. The United States Nuclear Regulatory Commission (U.S. NRC) offered to arrange the preparation of a comparative summary for CSNI based on responses to a questionnaire circulated by the OECD-NEA among member countries. The following report is based upon the information obtained from nine countries currently operating pressurized water reactors (PWRs).

BLANK PAGE

ACKNOWLEDGEMENT

The assistance is acknowledged of the representatives in the OECD-NEA member countries who prepared the responses to the questionnaire on which this report is based.

BLANK PAGE

CONTENTS

PREFACE iii

ACKNOWLEDGEMENT v

INTRODUCTION 1

TUBE PLUGGING CRITERIA 3

QUESTION 1A 3

QUESTION 1B 5

QUESTION 1C 5

SUMMARY DISCUSSION ON QUESTIONS 1A, 1B, and 1C 6

QUESTION 1D 7

QUESTION 1E 9

INSPECTION FOR STEAM GENERATOR TUBE DEGRADATION 13

QUESTION 2A 13

QUESTION 2B 14

QUESTION 2C 15

QUESTION 2D 16

SUMMARY DISCUSSION ON QUESTIONS 2A, B, C, AND D 17

STEAM GENERATOR TUBE REPAIR 19

QUESTION 3A 19

QUESTION 3B 20

QUESTION 3C 20

QUESTION 3D 21

SUMMARY DISCUSSION ON QUESTIONS 3A, B, C, AND D 22

DESIGN BASIS FOR STEAM GENERATOR TUBE INTEGRITY 25

QUESTION 4A 25

QUESTION 4B 26

SUMMARY DISCUSSION ON QUESTIONS 4A AND 4B 27

CONCLUSIONS. 29

REFERENCES 31

APPENDIX A - COPY OF ORIGINAL QUESTIONNAIRE A.1 33

APPENDIX B - EXTENDED INFORMATION FROM U.S. NRC RESPONSE
INCLUDES RESPONSES FROM QUESTIONS 1E AND 2B. B.1 41

APPENDIX C - CANADIAN REGULATORY CRITERIA
(APPENDED TO QUESTIONNAIRE RESPONSE) C.1 49

APPENDIX D - FRENCH GUIDELINES FOR IN-SERVICE INSPECTION OF
STEAM GENERATOR TUBING
(APPENDED TO QUESTIONNAIRE RESPONSE) D.1 52

FIGURES

1.	Causes of Steam Generator Tube Plugging	10	
B.1	Eddy Current Indicated Defect Depth Versus Actual Depth for EDM Slot Specimens	B.3	43
B.2	Eddy Current Indicated Defect Depth Versus Actual Depth for Uniform Thinning Specimens	B.3	43
B.3	Eddy Current Indicated Depth Versus Actual Depth for Elliptical Wastage Specimens	B.4	44
B.4	Depth Indications of Eddy Current Tests Versus Burst Pressure for All Tube Geometrics	B.4	44
B.5	IGA Tube Burst Test Data - Laboratory Defects	B.5	45

BLANK PAGE

X

TABLES

1. Countries/Organizations Responding to Questionnaire on Steam Generator Tube Plugging Criteria 2

2. Typical Plugging Limits for U.S. Plants 4

INTRODUCTION

The following report presents a summary and comparison of responses received to an a questionnaire distributed by the Organization for Economic Cooperation and Development-Nuclear Energy Agency (OECD-NEA). The questionnaire covered pressurized water reactor (PWR) steam generator tube plugging criteria and practices. The purpose of the study was to determine what tube plugging criteria are being used and what the technical bases are for these criteria. The questionnaire, a copy of which is provided in Appendix A, addressed four related areas: 1) Tube Plugging Criteria, 2) Inspection for Steam Generator Tube Degradation, 3) Steam Generator Tube Repair, and 4) Design Basis for Steam Generator Tube Integrity. Ten responses were received to the questionnaire, representing nine countries; a list of respondents is provided in Table 1. To broaden the information base contained in this report, U.S. utility practice as outlined in an Electric Power Research Institute (EPRI) summary report (Rau, Derbalian, and Thomas 1983) and a Statement of Work to a current EPRI program addressing tube plugging criteria[a] were used in comparative analyses of the questionnaire responses.

There was a fair range to the level of detail provided by the various questionnaire respondents. Answers ranged from of a single word up to several typed pages. This has, in some cases, made it more difficult to ascertain and compare the bases for particular positions relating to inspection and plugging of PWR steam generator tubes. In a few cases, clarification or expansion of a response has been sought from respondents. However, this report is primarily a compilation and comparison of the original responses. At times we have summarized the sometimes extensive material provided in the completed questionnaires. The intent was to provide the apparent meaning of the response as best as possible. When the answer provided was somewhat unclear we have included additional words in parenthesis, which represent our interpretation of the response. Where answers to different questions within a single questionnaire provided possibly conflicting information, this was pointed out in the discussion sections. The two responses from Japan were in close agreement and were consolidated in the response listings.

The report is organized so that it parallels the order of the original questionnaire. Each question is individually addressed and the answers compared in the discussion section either following the specific question or following all the questions on a given topic.

Of the nine countries responding, seven have primarily vertically oriented 'U-tube' type recirculating steam generators, generally tubed with either Inconel 600 or Incoloy 800. The Finnish steam generators, of Russian manufacture, are horizontally oriented and are tubed with austenitic tubing. One Canadian reactor has generators tubed in Monel, one plant has Inconel 600 and the remainder utilize Incoloy 800. In the U.S., PWR steam generators include both recirculating 'U-tube' type and straight through type, all are

---

(a) Statement of Work to EPRI contract RPS 404-5 "Steam Generator Plugging and Tube Sleeving Criteria."

vertically oriented and, except for one plant with austenitic stainless steel tubing, all are tube with Inconel 600.

TABLE 1. Countries/Organizations Responding to Questionnaire on Steam Generator Tube Plugging Criteria

COUNTRY	ORGANIZATION
BELGIUM	VINCOTTE
CANADA	ATOMIC ENERGY OF CANADA
FINLAND	FINNISH CENTRE FOR RADIATION AND NUCLEAR SAFETY (STUK)
FRANCE	COMMISSARIAT A L'ENERGIE ATOMIQUE
GERMANY	KRAFTWERK UNION AG
JAPAN	JAPAN ATOMIC ENERGY RESEARCH INSTITUTE
JAPAN	JAPAN POWER ENGINEERING AND INSPECTION CORPORATION
SPAIN	CONSEJO DE SEGURIDAD NUCLEAR
SWITZERLAND	SWISS FEDERAL NUCLEAR SAFETY INSPECTORATE
UNITED STATES	U.S. NUCLEAR REGULATORY COMMISSION (NRC)

TUBE PLUGGING CRITERIA

QUESTION 1A

What are the current tube plugging criteria for regulation of steam generators? (For example, 40% of tube wall loss)

Responses

Belgium: 40% nominal tube wall loss.

Canada: Anticipated wall loss which would exceed 40% of nominal wall prior to next inspection must be submitted to authority for disposition.

Finland: No detailed plugging criteria have been established (due to lack of degradation experiences). Indications >20% must be reported and evaluated. Plugging criteria are to be developed on a case by case basis.

France: 40% for straight sections of tube.

Germany: Normally 50%. In very special cases (abnormal degradation phenomena) in conjunction with the authority lower values have been used.

Japan: 20% maximum; any indication attributable to intergranular attack (IGA) or stress corrosion cracking (SCC).

Spain: 40%

Switzerland: 50%

United States: Generally 40%, however, criteria are established on a plant by plant basis, in the plant technical specifications. The plant technical specifications are subject to change based on operating and degradation history. Exampies showing plant-specific plugging criteria are provided in Table 2.

Discussion

As indicated above there are a range of criteria for plugging a tube. Two of the responses did not indicate specific plugging criteria, but instead conditions under which the regulating authorities would be notified for further evaluation. While the German response to this question indicated a general plugging criteria, later statements in the questionnaire indicated that there is no set plugging limit and that each degradation phenomenon is subject to evaluation by the authorities. One Japanese response indicated that significant changes in eddy current signals from examination to examination were cause for plugging, though it wasn't clear if this was a regulatory position or a general utility practice. Several of the responses indicated (in this question or elsewhere in the questionnaire) that plugging criteria are subject to re-evaluation with experience. In the U.S. this has generally led to a plugging criterion with a decreasing amount of wall loss. For example, many of the original U.S. plant technical specifications allowed 50% nominal wall loss before plugging. Most of these plugging criteria were reduced to

TABLE 2. Typical Plugging Limits for U.S. Plants

Plant	SG Model	Plugging Limit (%) Tubes	Sleeves
San Onofre 1	W 27	50(1)	40
Ginna	W 44	40	30
Point Beach 1, 2	W 44	40	40
Indian Point 3	W 44	40(2)	40
Summer	W D3	40(3)	-
Palisades	CE	64(4)	34(4)
Millstone 2	CE	40	Note (5)
Three Mile Island 1	BW	40	-

(1) In addition to this Technical Specification limit, the utility has committed in previous inspections to plug all non-sleeved tubes containing intergranular attack (IGA) indications at the top of the tubesheet elevation. If the IGA indication exceeds 50%, then all adjacent non-sleeved tubes would also be plugged as a conservative precaution.

(2) A 65% plugging limit was approved for application to pit type defects only during one cycle of operation (i.e., cycle 4). Tubes with pit type defects exceeding 40% were subsequently plugged or sleeved prior to the next cycle of operation.

(3) Limit does not apply to indications located at least 1.6 inches (i.e., F* distance as defined in Westinghouse Reports WCAP 11228 and WCAP 11229, "Tubesheet Region Plugging Criteria") below the top of the tubesheet (or from top of last hardroll, whichever is lower). See response to question 1C for additional details.

(4) An operating allowance, as approved by the NRC, must be subtracted from these values to determine the plugging limit.

(5) Plugging limit for sleeves will be incorporated into Technical Specifications prior to next refueling cycle.

40% as the plants switched from phosphate secondary side water conditioning to an all volatile treatment (AVT) (Rau, Derbalian, and Thomas 1983). There have been other instances in the U.S., however, where particular defect types in specific locations were temporarily granted higher tube plugging criteria than the general plant technical specifications. These later criteria usually provide for interim operation to permit optimally scheduled repair.

In addition to the above information, two of the responses indicated a leak rate criterion was applicable. This issue was not specifically addressed in the questionnaire; however, answers to other questions specifically mentioned allowable leakage in the tube sheet crevice region and of axial cracks in the roll transition.

QUESTION 1B

Are the tube plugging criteria defect-specific? (For example, do stress corrosion cracks have different plugging limits in the regulations than pits or wastage?)

Responses

Belgium: Not defect-specific.

Canada: Not defect-specific.

Finland: Degradation handled on a case by case basis.

France: Yes, criteria are defect-specific.

Germany: Yes, criteria are defect-specific. Criteria mainly depend on the anticipated annual growth of the degradation (main degradation was wastage, 50% plugging criteria).

Japan: Yes, criteria are defect-specific.

Spain: Not defect-specific, with one exception (see discussion).

Switzerland: Not defect-specific.

United States: Typically not defect-specific, some exceptions (see discussion).

Discussion

Most respondents provided only very brief answers to this question, allowing limited evaluation of their response. There seems to be an almost even division of responses to the above question. Three countries indicated defect-specific plugging criteria, and five countries indicated plugging criteria are not defect-specific (with limited exceptions in two cases).

The Japanese response stated that intergranular attack (IGA) and stress corrosion cracking (SCC) indications were handled more severely (all are plugged) than general wall loss indications (wastage). The French response provides an example of a plugging criteria based on length for axial cracks at the tube roll transitions. The plugging limit for these defects is 16 mm in length. The U.S. response indicated that the Nuclear Regulatory Commission (NRC) staff actions have allowed for instances of defect-specific plugging criteria. These instances are plant specific, and usually temporary until a remedial action such as sleeving can be performed. The general U.S. criteria are not defect-specific. The Spanish response allowed that SCC in the tube sheet crevice is handled differently (no specifics provided). The German response, taken with the response from section 1D of the questionnaire, states that all defect phenomena are treated individually. This implies that the evaluation of different defect types results in different plugging decisions.

QUESTION 1C

Do the tube plugging criteria depend on defect location in the generator? (For example, are defects in straight tube sections treated differently from defects in the U-bends?)

Responses

Belgium: No, not location-dependent.

Canada: No, not location-dependent.

Finland: Degradation handled on a case by case basis.

France: Yes, location-dependent.

Germany: Yes, because of special phenomena which have been found in only a few steam generators.

Japan: No, not location-dependent.

Spain: No, not location-dependent (with one exception-see discussion).

Switzerland: No, not location-dependent.

United States: No, not location-dependent (with possible exceptions).

Discussion

As in the previous question the responses provided were in general one word or very brief. Four of the responses stated no location dependence for tube plugging, with another two responses indicated this was the general position with exceptions. One response implied case by case decisions and the remaining two responses stated the tube plugging criteria were location-dependent.

The Spanish response provided that stress corrosion cracks in the tube sheet crevice were handled differently than the general criteria. The respondent noted that location of the crack within the tube sheet rather than crack depth governed the plugging decision. No further information was provided as to the criteria by which this defect type/location was treated. The French response gave an example of the 'U-bend' transition zone as having location specific criteria. The French have a straight tube section plugging criterion of 40% degradation. How this criterion is modified for other than straight sections was not provided in the questionnaire response. It was also not clear whether a defined regulatory position exists, but instead it appears that the regulatory authorities evaluate specific instances individually where the 40% criterion does not apply. While the Belgian response to this question was negative, elsewhere in their responses to the questionnaire it was stated that cracks (including leaking cracks) in the tube sheet and through wall axial cracks associated with "kiss" rolling (roll transition region) were acceptable.

SUMMARY DISCUSSION ON QUESTIONS 1A, 1B, AND 1C

The issue of defect-specific plugging criteria appears to have four elements: location within the generator, ability to nondestructively determine defect type, accurate knowledge about defect growth rates, and the potential consequences of the particular type of degradation (e.g., in terms of tube leakage or rupture). Based on our experience and literature documentation (Rau, Derbalian and Thomas 1983)(a) the lack of defect-specific plugging criteria

---

(a) Statement of Work to EPRI contract RPS 404-5 "Steam Generator Plugging and Tube Sleeving Criteria."

is largely affected by limitations of eddy current nondestructive inspection to adequately characterize specific defect types. Nondestructive examination (NDE) limitations have, in several cases, led to plugging practice more stringent than the general plugging criteria. For example, where NDE signals may, by location or signal pattern, potentially be attributable to a crack, tubes are generally plugged. This is primarily associated with evidence that eddy current NDE often does not reliably detect and size SCC. Defect-specific criteria have sometimes been used when additional defect type information has been obtained such as from tube pulls. Plugging criteria have occasionally been modified when the probability or consequences of tube failure have been judged to be acceptably low. Examples are: 1) temporary relief from a more stringent general criteria, granted for pitting (U.S.); 2) temporary relief from a more stringent criteria, granted for IGA within the tube sheet crevice (U.S.); and 3) a criteria based on crack length, apparently allowing through wall defects to remain in service, for the roll transition region (France, Belgium).

A general trend exists toward plugging any defect found in a region where cracking is the historical degradation mechanism and there is no structural confinement such as in the tube sheet crevice. An example of this trend is the move towards conservative plugging practice for NDE indications found in the bend transition on U-bends. The motivation for this trend is affected not only by uncertainties in NDE defect characterization but also by evidence that SCC growth rates may be very high.

QUESTION 1D

Are there examples of tube plugging criteria being used by utilities that are different from the regulatory requirements? Please state examples. (For example, it is common field practice to plug U-bends with defect indications, regardless of size, since they are assumed to be stress corrosion cracks that may grow through wall in a short time. This differs from the regulatory tube plugging criterion of 40% wall degradation.)

Responses

Belgium: Yes. An example is preventative plugging of first row U-bends. Utilities may also depart from the regulatory requirement, allowing any length axial crack and most circumferential cracks located a sufficient distance below the secondary side within the tube sheet. Cracks (including through wall) in the roll transition, kiss roll, are also not subject to the standard plugging criterion.

Canada: It is conceivable that utilities might plug below the 40% criterion; however, the situation has not yet been encountered due to excellent tube reliability record.

Finland: No degradation experience.

France: Yes. Example provided in 1C. referred to, concerning plugging indications in the U-bend roll bend transition region.

Germany: Generally no, since there are no explicit plugging criteria in the German regulatory requirements (KTA 3201.2 Safety Rule must be considered). New degradation phenomena must be discussed with the authorities.

Japan: Yes. Preventative plugging where no countermeasures for tube degradation can be taken.

Spain: No. Though dented tubes preventing probe passage have been plugged in some cases.

Switzerland: Yes. An example is one utility plugging or repairing all indications in the tube sheet.

United States: Yes. There are many examples of utility initiated plugging; however, since these are individual decisions they are not implemented at all plants. Examples provided: 1) plugging of all row one U-bends because of a high potential for stress corrosion cracks; 2) plugging of all detectable U-bend indications regardless of depth; 3) plugging in response to denting; 4) plugging below technical specification limits due to NDE measurement uncertainties of IGA at the top of tube sheet.

Discussion

There appears to be a general consensus that utilities plug tubes in addition to those required by the regulatory criteria. The German response indicates that all types of degradation are brought to the attention of the authorities. This response implies that utilities in Germany do not plug tubes without prior regulatory concurrence. Other portions of the French response indicate a very similar philosophy: plugging decisions are made on a case by case basis with the authorities. Responses from Canada and Finland indicate that the situation has not occurred, though the Canadian response allows that utility-initiated preventative plugging could occur.

Based on the U.S. NRC response and on Rau, Derbalian, and Thomas (1983), utility-initiated actions in the U.S. have been extensive. The operating experience in the U.S. encompasses a number of plant design variations, an extended range of service life, and secondary side water chemistry control that can vary considerably from utility to utility or plant to plant. Figure 1 (Pathania and Balakrishnan 1986) shows the percentage of tubes plugged in U.S. units caused by various forms of degradation on a yearly basis. What is apparent from this figure is the evolutionary nature of steam generator tube degradation. The history of tube degradation shown in this figure is not only affected by initiation and growth rates. Changes in operating conditions, such as from phosphate to AVT secondary side water chemistry, address the problem of wastage, but cause another problem, denting. Generator design changes eliminate certain problems in newer plants or replacement units (e.g., the change from drilled hole carbon steel support plates to eliminate denting problems).

The general U.S. utility practice in plugging beyond the NRC criteria, seeks to avoid unscheduled outages necessitated by cumulative leakage exceeding the plant technical specifications. An early example of preventative plugging was removal of tubes from service which were subject to severe deformation by denting, such as those near the soft spots (flow slots in the tube lane) and

hard spots (anchoring blocks and wedges at the periphery of the tube support plates). Several units plugged first row tubes, due to the high potential for stress corrosion cracking in the small radius U-bends. Plugging of any U-bend indications (regardless of size) has occurred, due to the potentially high rate of stress driven crack growth. There is also some uncertainty concerning the detection limits and sizing capabilities for cracks, especially in the curved U-bend tube geometries. Preventative plugging has also been practiced to some extent for tube sheet crevice indications, for the most part believed to be IGA and/or SCC. Here utility initiated plugging appears to be largely driven by a desire to remain within leak rate limits, and stems from uncertainties associated with defect characterization by NDE. Utilities have plugged dented tubes based on whether a particular size NDE probe could be passed through the tube. This criterion has served to both remove tubes from service that could not be adequately inspected and reduce the probability of initiating SCC in highly strained sections of tubing. Recently, alternative criteria based on profilometry determined maximum tube strain have been proposed as an effective means for determining when to plug a dented tube.

Rau, Derbalian, and Thomas (1983) define a leakage occurrence rate (LOR) as number of tube leaks divided by the number of in-service tubes times reactor critical days. The plant-specific LOR values given in that report generally increase as new degradation mechanisms appear and then decrease with improvements in utility tube plugging practice. The report is unclear as to how many of these improvements in utility practice involved NRC action. The fact that LOR increases for each new degradation type seems to imply that eddy current inspection methods do not generally find the new defects prior to leakage occurrences. After identification of a new defect, the inspection procedure is often modified to address the new problem. This usually results in improved inspection performance and decreased leakage rates because tubes are plugged before through-wall penetration of the defect. The data show a trend in tube plugging practice which has generally become more conservative with plant age.

QUESTION 1E

What are the technical bases for the tube plugging criteria? Please provide references. (For example, current U.S. tube plugging criteria were derived from a model of remaining tube integrity as function of wall loss for a wastage defect. The tube plugging criteria include a factor for increased defect enlargement between inspections and another factor for uncertainties associated with the NDE inspection reliability).

Responses

Belgium: Tube leakage plugging criteria are based on radioactivity release limitation. The 40% wall loss plugging criterion is based on a model of remaining tube integrity for wastage degradation, as is done in the U.S. The acceptance of stress corrosion cracks in tube sections within the tubesheet is based on the lack of safety-related problems, verified by theoretical analysis and experiments. The acceptance of axial stress corrosion cracks in the kiss roll transition zone is supported by the fact that the measured crack lengths are small. This acceptance is consistent with the spirit of

the (U.S. NRC) Regulatory Guide 1.121 which basically is not opposed to the acceptance of through wall cracks.

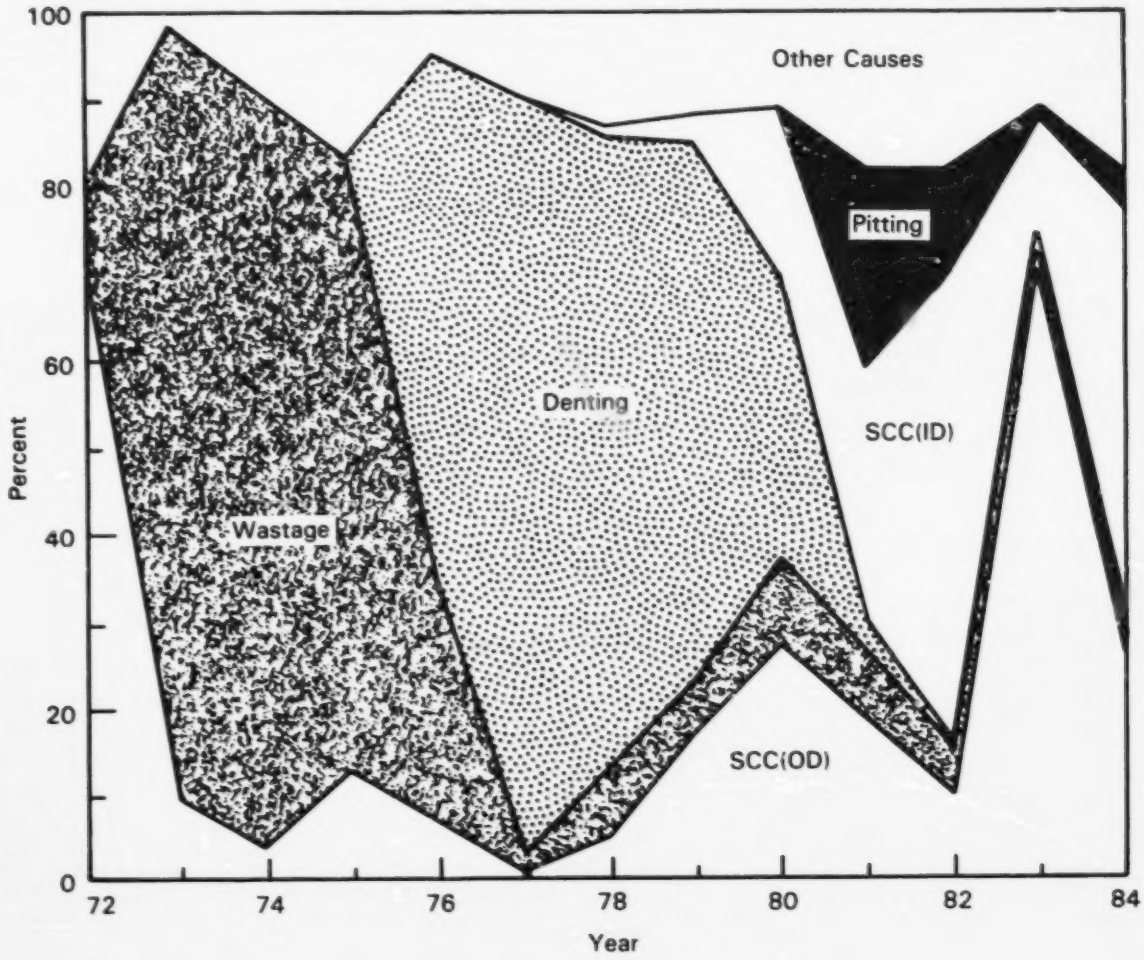


FIGURE 1. Causes of Steam Generator Tube Plugging (Pathania and Balakrishnan 1986)

Canada: Present requirements are that indications of 20% or greater depth of tubing wall thickness be recorded and reported. The onus is then placed on the operator to address anticipated wall loss prior to the next inspection; when this exceeds 40% of the nominal wall thickness, the operator submits the proposed disposition to the authority. Although this situation has not yet occurred for CANDU steam generator tubing, we expect that the technical basis for the tube plugging criteria that would be proposed by the operator would be that the structural strength of the tube with the defect meets structural requirements for the tube location(s) and defect location(s) in question. Increased defect enlargement between inspections and uncertainties associated with NDE inspection reliability would be addressed in the proposed disposition.

BEST COPY AVAILABLE

Finland: No detailed tube plugging criteria established, shall be determined on a case by case basis when the need arises.

France: Technical bases: Calculation, tests including burst tests, justifying tube plugging criteria, based on wall loss or length and depending on the nature of the defect. Reference: SFEN meeting, Paris April 4, 1986.

Germany: The plugging criteria are based on tube integrity considerations as a function of wall loss found by tests. The criteria include also a factor for increased defect enlargement between inspections and a factor for inspection technique uncertainties as well as safety factors according to German requirements KTA 3201.2. Response refers to operating experience, laboratory analyses/tests and tube pulls as reference for bases.

Japan: The (tube plugging) criterion of 20% for wastage is based on the quantitative evaluation limit for eddy current testing, obtained (experimentally determined) using many kinds of artificially machined defects. Also considered is the amount of scattering in measured values, which depends on the kind of defect. In fact, it is so difficult to make quantitative judgments on the defect signals that all tubes having defect signals are usually plugged or sleeved.

Spain: In the portion of the tube outside of the tubesheet the technical bases are similar to the current U.S. tube plugging criterion. For the defects within the tubesheet the technical basis is to prevent the extraction of the tube end outside of the tubesheet.

Switzerland: The plugging limits are based upon the minimum tube wall thickness necessary to provide adequate structural margins during normal operating and postulated accident conditions. These limits allow for eddy current uncertainties and incremental wall degradation which may occur prior to the next in-service inspection of the tube.

United States: Regulatory Guide 1.121, "Bases for Plugging Degraded PWR Steam Generator Tubes," defines an acceptable basis for developing steam generator tube plugging criteria which are included in the Technical Specifications of each operating plant. The Regulatory Guide specifies the margins of safety and loading conditions to be considered in establishing the tube plugging criteria. In addition to the factors of safety required on stress, an additional thickness for degradation during operation and eddy current test (ECT) error is required to be added to the calculated minimum acceptable tube wall thickness. This approach is intended to ensure that tubes will maintain the minimum acceptable wall thickness until the next inspection.

It is important to note that the minimum wall requirements are based on very conservative calculations. These calculations generally assume the degradation to involve uniform thinning of the tube walls in the axial and circumferential direction. Actually, operating experience indicates that most flaws tend to involve relatively short axial and/or circumferential dimensions. Further, plugging limit calculations are typically based on the ASME Code minimum material properties. A tentative conclusion is that existing plugging limits (typically 40%) are adequate to ensure tube integrity provided that degradation rates between inspections are not excessive. This appears to be true primarily because conservatisms implicit in the calculated

minimum wall requirements more than compensate for potential non-conservatisms concerning the allowance for eddy current error.

The U.S. NRC provided an extensive response to this question, including an example plugging criteria calculation and data on eddy current accuracy. This information is provided in Appendix B.

Discussion

All responses appear to agree that the tube plugging criteria outside of the tube sheet region is governed by maintaining tube integrity of the degraded tube. Tube integrity determinations are apparently extensively supported by both theoretical and empirical (burst, collapse, leak rate) studies. The responses in general indicate that the issue of degradation rate during the period between inspections and the issue of (eddy current) NDE uncertainty/reliability must be factored into plugging decisions. Likewise, in general, there appears to be strong reference to operating experience in making decisions. However, there isn't a consensus on what the resulting tube plugging values should be (witness previous part 1 answers). Although it is mentioned that different defects will have different effects on tube integrity, it is also apparent from the responses to other questions that defect type identification poses a problem.

There does not appear to be a consensus on the issue of tube plugging criteria in the tube sheet region. Several respondents are prepared to allow stress corrosion cracks, including through wall cracks, within the tube sheet to remain unplugged. Other respondents, as noted by the U.S., retain a leak rate criterion which would appear to not allow significant leakage, even in the tube sheet region.

INSPECTION FOR STEAM GENERATOR TUBE DEGRADATION

QUESTION 2A

What are the in-service inspection requirements to determine steam generator tube degradation? (Instrumentation, procedures, extent and periodicity requirements)

Responses

Belgium: Schedule and sampling requirements are provided in (plant) technical specifications and are based on the philosophy of (U.S. NRC) Regulatory Guide 1.83. Inspection method and procedures agree with ASME Code, Section XI or must be demonstrated to be superior.

Canada: Schedule and sampling requirements are per CSA N285.4 for extent and period. (A copy of this specification, provided in the Canadian response, is included as Appendix C). In summary, the inaugural inspection should include a minimum of 1.5% of total tubes in one steam generator. Subsequent periodic inspection requires not less than 1% of the total number of tubes in one steam generator. Tubes to be inspected include those deemed subject to the most severe service and those having significant previous indications of degradation. There is also a requirement to inspect tubes adjacent to leaking tubes. Inspection by eddy current or an equivalent method is allowed in compliance with ASME, Section V, Article 8. Equipment used varies, the CANSCAN system was given as an example.

Finland: ASME Code, Section XI inspection requirements.

France: The French response included a several-page document outlining the philosophical approach used in French regulation. (This document is provided in Appendix D). To summarize: a flexible regulatory approach is used whereby the objectives are defined and the operator is responsible for establishing the means to reach the objectives. The overall objective is to be able to discover degradation during service that may be detrimental to plant safety. Operators define inspection methods and reliabilities with Safety Authority approval. Periodic inspection intervals are less than 2 years, with complete inspections at 30 months and a minimum of once every 10 years. Sampling rate is a function of previous degradation experience and current inspection results. Tubes are inspected from inlet to outlet. Inspection is by multifrequency eddy current, with the use of special eddy current probes and supplemented by validation through tube pulls.

Germany: Plant specific tube inspection programs discussed with the authority and Technischer Uberwachungs-Verein (TUV). Basis is the German KTA 3201.4

- 10% of all tubes within 4 years
- areas with high corrosive attack known from operational experience
- tested tubes have to be changed to cover nonsystematic defects

Multifrequency/multiparameter methods are used. General degradation >20% must be recorded in accordance with KTA 3201.4. In many cases, the extent of inspection has been much higher than 10% in 4 years.

Japan: Inspections are conducted on all tubes, full length, every 12 months. Multifrequency eddy current is used per MITI Standard similar to ASME section V. If no degradation experienced, a 30% inspection of each generator is allowed on alternate annual inspections.

Spain: Minimum requirement of ASME Code Section XI and (U.S. NRC) Regulatory Guide 1.83. Extent of inspection is larger in practice. Multifrequency eddy current inspection.

Switzerland: In each three-year interval, 3% of the tubes of a steam generator must be tested. Multifrequency eddy current techniques are used.

United States: Minimum requirements concerning instrumentation and procedures are specified in ASME Code, Section V, Article 8 - Appendix I and Section XI, Appendix IV (Summer 1983 edition). The extent and periodicity of inspections are specified in plant Technical Specifications. NUREG-0103, -0121 and -0452 were referenced as providing standard specifications for each of the U.S. PWR vendors. The NRC response noted that Brown, 1985, provides excellent guidance and recommendations for eddy current inspection programs.

QUESTION 2B

What accuracy and precision are associated with the required in-service inspection procedures and instrumentation? In other words, what is the reliability of the NDE method to detect and size defects? What are the bases (experimental/theoretical) for these reliability estimates? Please provide references if available.

Responses

Belgium: The accuracy of the inspection technique varies depending on the type and location of the defects. Local thinning >10% is detectable. However, the bobbin coil can miss defects such as through wall stress corrosion cracks, especially at geometrical discontinuities. Accuracy estimates are based on experience and destructive examinations.

Canada: We are reasonably confident that present eddy current technology will reliably identify significant tube degradation. The accuracy of the techniques for depth determination varies with the type of defect but is felt to be limited to approximately ±10% to ±15% of the wall thickness. The reference specimen for Canadian inspections is described in Appendix C.

Finland: ASME Code, Section XI is followed for calibration. Tests have been conducted on artificial defects such as cracks, and dents and (the effects of) bends.

France: Detection and sizing depend on the nature and shape of defects.

Germany: The accuracy is ±10% of wall thickness considering all degradation phenomena (detection mode). This can be improved with further sizing technique. Reliability estimates are based on laboratory examinations of pulled and simulated degraded tubes. Stress corrosion cracking was not observed up to now.

Japan: Wastage type degradation, >20% wall loss is detectable with an error of depth estimation of ±10%. On laboratory simulated SCC, >20% of wall depths were detectable. Bases for accuracy estimates are laboratory tests on artificial defects. Efforts are underway to increase reliability through use of special probes, multi-frequency (mixes) and computerized analysis.

Spain: For fretting, (laboratory) studies demonstrate an accuracy of 10%. Precision can't be predicted in advance for any defect. Studies must establish precision for each defect as it becomes an issue.

Switzerland: The reliability of the eddy current method depends on the type of the failure in the tube. The accuracy of the eddy current method is ±5% for wastage, ±10% for fretting, and >±10% for cracks. This is verified by ultrasonic tests and experiments on pulled tubes.

United States: The reliability of ECT to detect and size defects is a strong function of the geometry, orientation, and volume of the defect; the defect's location relative to extraneous sources of noise; the type of eddy current equipment employed; and the training, experience and alertness of the data evaluators. It is important to note that adherence to minimum requirements as specified in the ASME Code does not ensure that ECT inspection programs will reliably detect and accurately size many of the kinds of defects occurring today. (Several pages summarizing experimental data were supplied indicating among other findings that crack depths may be underestimated by as much as 10% to 40%). Concerning calibration of equipment the response states, "the ASME calibration standard is designed to verify consistent eddy current system response. It does not establish optimum working sensitivity in all cases nor does it provide for the best estimation of the depth of tube wall discontinuities under all circumstances." Due to the extensive nature of the U.S. NRC response, significant portions are provided in Appendix B.

QUESTION 2C

Does the required NDE inspection technique reliably identify the type (e.g., cracks, pits, wastage, fretting, etc.) of tubing degradation? Is this required? What methodology is used?

Responses

Belgium: The regulatory inspection technique does not allow the identification of the type of tubing degradation. Some characteristics can be determined from location and the amplitude and phase of the signal.

Canada: Eddy current testing alone does not allow the type of wall degradation to be identified. This distinction is made based on experience, judgment and other information such as defect location. There is no requirement to identify type of degradation, but it is done when possible.

Finland: Answer refers to ASME Code Section XI.

France: Answer refers to document included as Appendix D. This document explains the philosophy and procedure by which in-service inspections are carried out. There does not appear (to the authors) to be evidence that defect type identification is made using standard eddy current testing.

Based on tube pull data and location information defect type identification is arrived at for the limited number of defect conditions found in French units.

Germany: Type of defect (wastage, fretting, pitting, cracking, OD and ID defects) can be identified approximately by the amplitude and length (shape) of indications with standard techniques. Better evaluations can be obtained with improved inspection techniques (rotating probes, ET/UT segmented probes) if necessary.

Japan: The type of degradation cannot be identified by the eddy current technique and it is not required to identify the type of degradation. Tube pulls are used to identify types and causes of degradation for previously unexperienced indication types.

Spain: The technique (eddy current testing) does not identify the type of tubing degradation.

Switzerland: Inspection technique does not identify degradation type. Identification is not required.

United States: Regulatory Guide 1.83 states in part "The equipment should be capable of locating and identifying stress corrosion cracks and tube wall thinning by chemical wastage, mechanical damage, or other causes". Simply meeting the minimum ECT inspection requirement of the ASME Code does not ensure the reliable detection and accurate sizing of all flaw types under all test conditions. We feel that the NRC response indicates the desirability of defect identification, but acknowledges that it is not possible using the regulatory required technique (single frequency eddy current) alone.

QUESTION 2D

What nondestructive inspection procedures are used in addition to those required? To what extent and how frequently are these alternative techniques employed? What improvement in characterization and sizing of defects do these techniques achieve?

Responses

Belgium: Rotating probe eddy current is used at the utilities discretion to inspect within the tubesheet and the roll transition zone. The technique provides an order of magnitude sensitivity improvement in detection and multiple defect discrimination.

Canada: Only eddy current testing is used. The general single frequency eddy current inspection is occasionally supplemented by alternate eddy current probes for the tube sheet and support plate regions. Multifrequency eddy current has been used.

Finland: Visual inspection of tube/tubeplate welds every four years.

France: Use of a rotating eddy current probe for the lower part of the tube.

Germany: Analyses with rotating ET/UT probes if indications show wall degradation >50% or growth if degradation >10%/y. For wastage degradation the sizing accuracy is improved to ±5% of wall thickness with these techniques. Also segmented probes (8 coils) are used for large numbers of tubes to be analyzed.

Japan: Only eddy current inspection is used. An application study of the electromagnetic transducer has recently been formed.

Spain: No other nondestructive inspection technique is required. Answer did not indicate if additional methods were used.

Switzerland: Ultrasonic inspection is sometimes used for comparison. Also, visual inspection of the tubes is sometimes carried out.

United States: The NRC staff has no information regarding the use of other inspection techniques apart from eddy current testing by any U.S. utility.

SUMMARY DISCUSSION ON QUESTIONS 2A, B, C, AND D

The responses indicate that the basic nondestructive characterization technique is eddy current testing. Several respondents indicate testing in accordance with the ASME Code, which presently specifies single frequency eddy current testing. It is apparent that, in general, multifrequency eddy current testing is used, with the possible exception of Canada. There was general agreement that the eddy current technique could not by itself determine defect type. Defect classification is largely obtained through tube pulls. Establishment of defect type between similar generator designs is largely based on defect location and operating experience. In addition to bobbin coil eddy current testing, several respondents indicated use of special eddy current probes, which are designed for specific defect characterization in a particular region of the generator. The rotating point probe was mentioned for inspection of cracking in the tube sheet crevice region and roll transition. Ultrasonic testing was indicated as an additional characterization method in the Swiss and German responses. One Japanese response mentioned study of EMATs (electromagnetic transducers) and the use of ultrasound. We are also aware of special eddy current probes for inspection of the inner row U-bends; of multiplexed pancake coils for detection of cracking, including circumferentially oriented cracks; and of other coil designs for detection of IGA in the tube sheet region. In the U.S., where denting is a problem in several units, profilometry has been developed, to allow determination of the deformed tube geometry and subsequent calculation of maximum strain. These calculated strains have been proposed as a basis for tube plugging based on a strain criterion. Tube strain leading to cracking, however, is also thought to be strain rate dependent.

The majority of respondents indicated that wastage or large volume metal loss type defects were detectable by eddy current tests between 10% and 20% wall loss, with precision estimates between ±5% and ±10% of tube wall. Respondents noted that cracking could not be well characterized, with some responses indicating difficulty in detection and a general acknowledgement that sizing was quite uncertain. Respondents also mentioned laboratory tests and comparison with metallurgically analyzed pulled tubes as means of determining NDE accuracy.

The extent of in-service inspection required appears to cover a broad spectrum. At one end is the Japanese program of 100% full-length inspection every twelve months. The minimum requirements of the U.S., Canadian and Swiss inspection plans provide for only a few percent examination on non-defected units, with additional inspection if degradation is found. The French and German responses indicate inspection plans are established for each unit in conjunction with the regulatory authorities, and are individualized to express operating history.

The extent of ISI in Germany is based on KTA 3201.4 and is utilized in plants of Siemens/KWU Standard Design. Additional inspections based on consideration of plant operating history must be performed in conjunction with the regulatory authorities.

The French approach to inspections, as expressed in the paper included as Appendix D is possibly (in end result) not much different from the U.S. approach. One should consider that the French units are all of the same basic design and manufacture, and that a single agency establishes operating procedures for all units. Thus, it is not unrealistic to postulate that the inspection plans at all units are possibly quite similar to one another.

STEAM GENERATOR TUBE REPAIR

QUESTION 3A

What are the regulatory requirements for the repair and return to service of degraded tubing?

Responses

Belgium: Repair shall be performed in accordance with the principles of ASME Code Section XI.

Canada: There are currently no governing specific regulatory requirements for repair of degraded tubing in CANDU steam generators. However, any time tubing is repaired, an inspection or test will be required as agreed to by the jurisdiction.

Finland: No criteria established due to no degradation to date.

France: Authors could not determine an answer to this question from the response.

Germany: Until now the necessity to repair a tube has not existed. Generally each repair situation would have to be discussed with the TUV and the authority, and a procedure qualification would have to be performed.

Japan: Either repair or plugging may be applied to a degraded tube. The new pressure boundary introduced by repair should have both mechanical integrity and leak tightness, (requiring) confirmation of the reliability of the material, design and installation procedure. Before the performance of repair and return to service of degraded tubes, utilities must obtain permission of a working plan from MITI and must make an inspection before use.

Spain: No tubes have been repaired in Spain at this date, and there are no regulatory requirements related to repair of damaged tubes.

Switzerland: No regulatory requirement for repair of degraded tubes aside from 50% wall loss criteria (for repair or removal from service).

United States: In general, plant Technical Specifications require that defective tubes be removed from service by plugging. However, the staff has approved Technical Specification changes at a few plants permitting sleeving as an acceptable repair alternative to plugging based on case-specific reviews of proposed sleeving programs and sleeve designs at these plants. The NRC does not have standard review guidelines for review and approval of proposed sleeve designs. In general, the staff has approved proposed sleeve designs on the basis that they were designed to the same requirement as the original steam generator tubing. The sleeve must be designed to maintain the integrity of the reactor coolant boundary for the full spectrum of normal operating, transient, and postulated accident conditions. The sleeve must also be designed to ensure a leak-limiting seal between the primary and secondary systems in the event that the repaired portion of the tubing

develops a 100% through wall defect. Satisfaction of these functional requirements is generally accomplished through extensive tests and analyses.

QUESTION 3B

What are the inspection requirements for repaired tubing?

Responses

Belgium: The sample of the tubes to be inspected should include all non-plugged repaired tubes. The repair should allow inspection to be performed on the repaired tubes as on the other tubes, but not necessarily by using the same technique.

Canada: Currently no specific governing requirements for inspection of repaired tubing.

Finland: No answer (No criteria established due to no degradation to date).

France: An answer to this question could not be determined from the response.

Germany: No special requirements exist because there has only been a need to plug tubes. Method and approach would be similar to normal inspection; the program to be discussed with the authority and the TUV.

Japan: The inspection requirements for repaired tubing are the same as for original tubing. In addition the sleeve repairs are (initially) inspected by: welded sleeves-weld inspection, hydrostatic test, eddy current test; mechanical type sleeve-hydrostatic test, eddy current test; braze type sleeve-ultrasonic test, hydrostatic test, eddy current test.

Spain: No answer (No criteria established due to no repairs to date).

Switzerland: The inspection requirements are the same as for other tubes.

United States: As is the case for the original tubing, sleeves must be designed to incorporate an inspectable geometry. Sleeved tubes are usually subject to the same inspection frequency and sampling requirements as unsleeved tubes.

QUESTION 3C

What kind of steam generator tubing repair has been used? How extensively (number of tubes/units)? Are there additional repair methods likely to be used in the near future?

Responses

Belgium: Tubing repair: 1) mechanical rerolling at the highest elevation of the original expansion (about 100 tubes on one steam generator); 2) explosive minisleeves installed in the roll transition zone (about 200 tubes on one unit); 3) nickel plating (thin electrolytic deposit) of the tube inner surface expanded zone plus roll transition region (about 80 tubes in one unit).

Remedies: 1) shot peening over the transition zone plus five roll passes in the hot leg (steam generators of 2 in-service units); 2) rotopeening a minimum of the full length of the expanded zone in the hot leg (steam generators in 2 units prior to service).

Canada: No in-service tubing repairs have been made on CANDU steam generators. Sleeving is a possible option in the longer term should significant defects occur near the tubesheet region.

Finland: No degradation to date. Only one tube plugged, due to fabrication defect.

France: Sleeving has been used on a few tubes for a limited period.

Germany: There has been no real case of tube repairing. As a precaution, KWU has developed a tube weld sleeve method and a partial tube replacement method.

Japan: Brazed sleeves have been applied to approximately 2500 tubes in 12 steam generators at four units. No additional repair methods are considered in the near future.

Spain: No answer (No repairs to date.)

Switzerland: A sleeving technique is used in two older plants.

United States: With one exception sleeving is the only method currently employed in the U.S. to repair defective tubes such that they may be permitted to remain in service. In excess of 16,000 sleeves have been placed in 10 plants. The one exception was repair of SCC in the upper 2 to 3 inches of the upper tube sheet of the TMI Unit 1 once through steam generator. This repair involved explosive expansion within the tube sheet (to below the defected area). We (NRC) are not aware of other steam generator tube repair methods under serious consideration by the U.S. industry at this time. Shot peening of tubes inside the tubesheet and insitu thermal treatment of U-bends are considered to be preventive measures rather than repair methods.

QUESTION 3D

What are the technical bases for plugging of repaired tubes? Have any repaired tubes been removed from service?

Responses

Belgium: No special requirement or plugging of repaired tubes. Some of the repaired tubes have already been plugged.

Canada: No repaired tubes. In general regarding steam generator tube repair, demonstration of fitness for service is an overriding requirement and is done on a case-by-case basis.

Finland: ASME Code, Section XI can be applied. (No repaired tubes).

France: When no defect indication is detected (in the tube repair) and when the results of removed tubes are satisfying (repaired tubes can remain in service).

Germany: No tubes repaired. Plugging would be based on (degradation) indications from eddy current or ultrasonic examinations.

Japan: When significant signals are indicated by ET at a higher elevation of the tubing than the position repaired already by sleeving, the tube is plugged since it is technically difficult to apply a further sleeve repair to a higher elevation. Otherwise no special plugging criteria for the repair.

Spain: No answer. (No repairs to date).

Switzerland: The technical basis for plugging repaired tubes is the same as for other tubes. No repaired tubes have been removed from service.

United States: To our (NRC) knowledge, there have been very few instances to date where the sleeves themselves became defective and had to be plugged. This is attributable to two factors: 1) corrective measures taken in parallel with the sleeving repairs to arrest or slow down the degradation rate, and 2) fabrication of sleeves from material with enhanced corrosion resistance relative to the original tubing material. Six sleeved tubes were plugged at Millstone 2 in 1985 as a result of sleeve indications. A number of sleeved tubes have been plugged prior to placing the tubes back into service, due to installation difficulties with the sleeves. The NRC response goes on to indicate no special need for evaluating how repaired tubes are plugged.

SUMMARY DISCUSSION ON QUESTIONS 3A, B, C, AND D

Of the nine responding countries, four have no repair experience and have apparently developed no criteria concerning repair techniques or inspection of repaired tubing at this time. The five countries indicating repair experience have all mentioned sleeving repairs. One country, Belgium, indicated non-sleeving remedial actions and repairs associated with the tube sheet region and the roll transition. It is our belief that the French are also conducting similar roll transition remedial or repair programs, though not mentioned in their response.

The only repair location mentioned in the responses involved the tube sheet region and roll transition in the tube sheet. It is our belief that additional repair methods (or remedial actions) and locations are under study if not already applied. These repair methods include the following.

1. Sleeving from the tube sheet region to above the sludge pile, possibly as high as the first tube support plate.

2. Partial tube replacement at or below the first support plate through the tube sheet. This method was mentioned in the German response as under study and has been demonstrated on the NRC's Steam Generator Group Project - Surry generator by a German group and by a U.S. group.

3. Sleeves which bridge tube support plates, possibly as a means of repairing IGA associated with these regions.

4. Possible replacement of degraded antivibration bars, again demonstrated on the NRC Surry unit.

5. EPRI sponsored research which has evaluated remedial stress relieving of U-bend regions.

Remedial actions are considered to be techniques that prevent or inhibit degradation, but are not applied to reduce or repair existing degradation.

For some respondents, the inspection of repaired steam generator tubes is essentially the same or has the same requirements as for unrepaired tubes. The Japanese response specifically mentions inspections of the repairs prior to return to service. (It is believed that this is universal practice, though not mentioned specifically in other responses). However, nowhere was there mention of post-service inspection procedures that are specific to the repair technique. For example, there was no indication that the sleeve pressure boundaries, e.g., the welded or brazed ends, when applicable, were specifically inspected at any point after the tube was returned to service. The Japanese response indicates that repaired tubes are subject to inspection at every annual inspection, though this would already seem to be the case since relief from 100% annual inspection is provided only for units not experiencing prior degradation.

Based on two responses (Belgium and U.S.), it is our conjecture that the generally accepted design criterion for repairs is to re-establish the undegraded properties of the original tube. The criteria for plugging of repaired tubes does not seem to vary significantly from the criteria for plugging of unrepaired tubes in most countries. The Belgian and Swiss responses state this as the case. The French response indicates that defect indications are investigated through tube removal to decide on required action, which is basically the same philosophy as their general tube plugging criteria. One of the two Japanese responses indicated sleeved tubes are plugged if a defect signal is detected in the sleeved portion. The U.S. response provides examples where the plant Technical Specification for sleeved tubes are identical to non-sleeved tubes, and other examples where the plugging criteria is 10% less through wall penetration for the sleeves.

BLANK PAGE

DESIGN BASIS FOR STEAM GENERATOR TUBE INTEGRITY

QUESTION 4A

What is the basis for the steam generator inspection program and removal of degraded tubing from service? (For example, establishment of a probability for single tube failure of $<10^{-6}$ per reactor operating year and probability for multiple tube failures of $<10^{-9}$ per reactor operating year). Provide documentation/references for establishing this basis.

Responses

Belgium: Confidence is made in the requirement of (U.S. NRC) Regulatory Guide 1.83 to lower the probability of tube failure. No estimate of the actual probability has been made so far.

Canada: The approach used in the CSA N285.4 standard clause 14 is to allow the periodic inspection program effort to concentrate on one steam generator. The tubes to be chosen for inspection are to include those which are considered to be subject to the most severe service. In practice this means that conditions such as those below are considered: 1) vibration, 2) erosion, 3) thermal shock, 4) sludge, 5) crevices, 6) low flow, 7) corrosion, 8) chemical attack, and 9) other consideration such as previous failure regions. Based on these considerations, specific tube locations in one steam generator are selected that are judged to be potentially subject to one or more of these conditions.

Finland: The basis is the requirements of ASME Code, Section XI.

France: From a general point of view, the steam generator inspection program is variable in periodicity, sampling rate and eddy current method used. For a particular steam generator, the inspection program fixes these above parameters, taking into account: 1) the defect characteristics, 2) the general results of the previous inspection, and 3) the results (if any) of tube removal examinations.

Germany: The basis for a steam generator inspection program is the operating experience. Tubes will be removed from operation after consideration of allowable tube wall degradation (based on burst and collapse tests) and depending on the kind of defects, the anticipated annual growth of defects, and the operating time between inspections. Tubes will also be removed from service if leakage is detected. No probabilistic criterion is used to remove tubes from operation.

Japan: The basis for inspection and repair including plugging is to keep steam generators in a no-leakage condition during plant operation.

Spain: The basis for inspection are (U.S. NRC) Regulatory Guide 1.83

Switzerland: Deterministic decision based on indications.

United States: Existing steam generator inspection requirements were developed (mid 1970s) primarily on the basis of experience and engineering

judgment on the expectation that these requirements would be effective in minimizing the frequency of steam generator tube ruptures (SGTRs). These requirements do not have a quantitative basis in terms of limiting the probability of single and multiple tube ruptures to specified limits. Risk studies to date (NUREG-0844 Draft Report for public comment) indicate that single and multiple tube rupture events are not dominant contributors to total core melt risk. Estimated probabilities for single and multiple tube ruptures are presented in NUREG-0844. It should be noted that the frequency of single tube rupture events is approximately 1.5×10^{-2} per reactor operating year, based on actual operating experience.

The low number of SGTR events are due only in part to existing in-service steam generator inspection requirements which are known to be far from fully effective in ensuring that all tubes vulnerable to rupture will be identified and removed from service before rupture occurs. Summarizing other parts of the response: the low SGTR rate is attributed to additional inspection activities carried out by utilities (beyond the minimum required) and to the leak before break characteristics of the steam generator tube materials. Most defects which are missed during inspection and subsequently grow through wall will leak prior to rupture. Leakage rate limits of 0.35 gallons per minute (for an individual steam generator) are based on test data which indicated that a through wall crack leaking at this rate will not rupture under normal operating, transient or postulated accident conditions. The 0.35 gpm limit applies to 75% of U.S. plants. All plants are currently implementing at least a 1.0 gpm limit on primary to secondary leakage.

QUESTION 4B

Describe empirical/theoretical information and models that have been developed to describe tube rupture, leak rates and in-service inspection reliability.

Responses

Belgium: An experimental program has been conducted to confirm available theories predicting the bursting pressure as a function of the geometrical and mechanical characteristics of the tubing material and the crack length. Reference: P. Hernalsteen, "Evaluation of Critical Sizes for Defects in Small Diameter Tubing," 7th International Conference SMIRT, Chicago 1983, Paper G/F-4/3.

Canada: A number of theoretical studies have been undertaken to calculate tube rupture leak rates under various CANDU steam generator conditions. Also leak characterization theoretical and experimental studies have been performed using thin wall steam generator tubes with different types of through wall cracks. The test series employed helium, low enthalpy and high enthalpy water. This leak characterization work was performed in support of the Bruce NGS-A steam generator leak location program.

Finland: None.

France: No separate answer provided.

Germany: Tube rupture/leak rate tests; burst and collapse tests. Reference: Azodi, D. et al. "On the Integrity of Steam Generator Tubes and Plugging Assessment," SMIRT 87 D/G 8 P.383. In-service inspection reliability is established by examinations of test specimens and removed service degraded tubes. Also, NRC's Steam Generator Group Project is used to verify ISI reliability.

Japan: Testing has been conducted to evaluate tube strength, rupture and collapse, and the effect of jet impingement from a leaking tube on neighboring tubes. Results: tube with 50% through wall defect has enough margin to withstand both operating internal pressure and external pressure during LOCA. Jet from leaker does not cause damage to the neighboring tubes during the time required for shutdown (20 hours maximum). Empirical data has been developed for in-service inspection (ISI) reliability, including repeat inspections varying probes used, inspectors, and time interval between inspections. Reference: "Summary Report of Proving Tests on the Reliability for Nuclear Power Plant - 1985".

Spain: No answer provided.

Switzerland: No answer provided.

United States: An effort in this area is being conducted by the NRC Office of Research as part of the Steam Generator Integrity Program/ Steam Generator Group Project. A major goal of this program is to determine the optimal frequency, extent of inspection and tube plugging criteria for specific types of ISI procedures utilizing presently available field-use eddy current NDE equipment and procedures. The program is also evaluating alternate or advanced NDE techniques for the ISI of steam generator tubes. Specific objectives of this program include:

- Completing the development of recommended revisions to Regulatory Guide 1.83. The work shall focus on development of an inspection plan to determine the extent, frequency and procedure for in-service inspection of steam generator tubes. The plan will consider the probability of tube failure between ISI periods; the reliability of eddy current and other NDE techniques to detect, characterize and size defects and the type, distribution and growth rates of different flaws in the generator.

- Completing the development of recommendations for revision of Regulatory Guide 1.121 concerning plugging of defective steam generator tubing. The revised plugging criteria will be based on burst and collapse test results of laboratory and service degraded tubes under normal operating and accident loading conditions.

SUMMARY DISCUSSION ON QUESTIONS 4A AND 4B

The responses to question 4A are somewhat difficult to compare because the respondents seem to have interpreted the question differently. One interpretation sought to describe how the current position on in-service inspection evolved with time. The other interpretation apparently was one of indicating the references to current inspection practices. Thus three of the respondents indicated conformance with the appropriate ASME pressure vessel code or

referred to U.S. NRC regulatory guides on tube inspection or tube plugging criteria. The French and Swiss responses briefly indicated how their inspection programs proceed.

The U.S. response went into considerable detail concerning the derivation of the present position on inspection and plugging. Basically the criteria evolved from a desire to minimize tube rupture events. (While not stated in the response, the major consideration was radioactivity release from the primary system). Leak rate criteria were based on leakage from a single through wall crack, again to avoid a tube rupture event. Inspection requirements to achieve this end (avoidance of tube rupture) were based on experience at the time, along with engineering judgments. While probabilistic interpretations of the risk of single or multiple tube failures have been made, there is no quantitative relationship between probability of failure and the inspection criteria. This probabilistic basis has been considered in the past and judged as economically unjustified. The U.S. response went on to indicate that re-evaluations of Regulatory Guides 1.83 and 1.121 are being conducted based on current experience and on more empirical data than was available when the Regulatory Guides were initially formulated.

The Japanese and German responses indicated an inspection and plugging philosophy based on achieving no leakage during service.

The Canadian response provided some development of philosophy, such as the U.S. response. Basically, inspection assumes a representative subset of tubes can be inspected to provide safe operation. Thus, based on engineering insight and experience, inspection is carried out on a single steam generator on tubes judged to have a higher probability for degradation. Although the Canadians have indicated only minor steam generator degradation, it is assumed that the Canadian philosophy is to use a single generator to detect generic degradation, then to check similar regions in other generators if degradation is found.

Responses to question 4B indicate that a number of countries have conducted their own theoretical and experimental studies relating to remaining pressure boundary integrity of degraded steam generator tubes. Test programs have included burst, collapse, and leakage rate studies. While the French did not separately respond to this question, we are aware of considerable French efforts in these areas. Several respondents also mentioned programs to establish NDE accuracy through studies on laboratory specimens, metallographic validation of pulled service degraded tubes, and repeat inspections of a set of tubes using different inspection equipment or staff. Considerable work in these areas has been recently conducted by the U.S. NRC's Steam Generator Group Project. The EPRI-led Steam Generator Owners Groups I and II have conducted extensive work on degradation identification and mitigation, with continuing EPRI programs addressing inspection issues.

As pointed out in the U.S. NRC response, it is felt that minimum inspection requirements are not responsible for the current low rate of tube rupture events. The response indicates that additional efforts by utilities along with the forgiving nature of Inconel 600 deserve considerable credit. The EPRI-recommended inspection guidelines were commented on as being beneficial.

COMMENTS

There were no additional comments provided by any of the respondents.

CONCLUSIONS

The preceding report was based on responses to an OECD-NEA questionnaire concerning pressurized water reactor (PWR) steam generator inspection and tube plugging criteria. For economic and safety reasons, a universal objective is recognized, that steam generator tube rupture events should be minimized. The inspection methods and the allowable degradation appear to vary from nation to nation. The major philosophical differences in approach appear to be well summarized in the French paper attached to their response and included in Appendix D. One approach is to deal with each degradation individually, involving the regulatory authority and the operator to evaluate further inspection and plugging on a case by case basis. The other approach is to define bounding requirements, within which each operator must perform, where the regulator becomes involved only by way of exception or special case. The regulatory environments differ between the various countries. Significant factors appear to be: the number of reactor operating agencies, consistency among operators and operations, the homogeneity of PWRs in the service base, the age of the reactors, and the number of operating units. Each of these factors play a role in arriving at the regulatory approach for each country.

BLANK PAGE

REFERENCES

1. Rau, S. A., G. Derbalian, and J. M. Thomas. 1983. "Steam Generator Tube-Plugging and Tube Sleeving Criteria: Assessment of Current Practice," EPRI NP-2921, Electric Power Research Institute.

2. Pathania, R. S. and P. V. Balakrishnan. 1986. "Correlation of Tube Support Structure Studies," EPRI-NP-4672, Electric Power Research Institute.

3. Brown, S. D. 1985. "PWR Steam Generator Inspection Guidelines," Rev. 1, Electric Power Research Institute.

APPENDIX A

COPY OF ORIGINAL QUESTIONNAIRE

APPENDIX A

OCDE

ORGANISATION DE COOPÉRATION ET
DE DÉVELOPPEMENT ÉCONOMIQUES

OECD

ORGANISATION FOR ECONOMIC
CO-OPERATION AND DEVELOPMENT

AGENCE POUR L'ÉNERGIE NUCLÉAIRE/NUCLEAR ENERGY AGENCY

38, boulevard Suchet
75016 PARIS
Tél. 45 24 82 00

RÉFÉRENCE

EN/S/1304

7th August, 1986

To: Members of CSNI Principal Working Group No. 3: Primary Circuit Integrity

Re: Review of Steam Generator Tube Plugging Criteria

At the meeting of Principal Working Group No. 3 held on 1st and 2nd July 1986, the Group agreed with a proposition from Mr. C.Z. Serpan of the United States that a comparative summary of steam generator tube plugging criteria used by Member countries would provide useful information to all participants. The United States Nuclear Regulatory Commission has an interest in the subject as a background to a current review of its Regulatory Guide 1.121, Bases for Plugging Degraded PWR Steam Generator Tubes. The Group accepted Mr. Serpan's offer to arrange for the preparation of a state-of-the-art report for PWG3 and CSNI, based on information provided by members through responses to a questionnaire. The information will be assessed and the report prepared at the Battelle Pacific Northwest Laboratory. The objective is to distribute the report well before the meeting of PWG3 planned for 30th September and 1st October 1987.

Members of PWG3 are invited to arrange for the completion of the enclosed questionnaire [SINDOC(86)140] with respect to practices in their country. It should be returned before 31st October 1986, to Mr. Rick KURTZ of the Battelle Pacific North West Laboratory, at the address shown on the cover sheet, with a copy to me at the OECD Nuclear Energy Agency. It would also assist if the tear-off reply slip was returned to me as soon as possible to advise us whether or not a reply to the questionnaire can be expected from your country, and from whom.

Your co-operation in arranging a response to the questionnaire by the reply date will be greatly appreciated and will help ensure that the final report is as comprehensive and useful as possible.

Yours sincerely,

Neil R. McDonald
Nuclear Safety Division

Enc.

CSNI PRINCIPAL WORKING GROUP NO. 3

QUESTIONAIRE ON STEAM GENERATOR TUBE PLUGGING CRITERIA

Please complete and return this form as soon as possible to:

Dr. Neil R. McDonald
Nuclear Safety Division
OECD Nuclear Energy Agency
38 Blvd. Suchet
75016 Paris
France.

☐ My country will complete and return the questionnaire by 31st October 1986*. This will be arranged by:

.....

☐ My country does not have information that it can provide on tube plugging criteria.

* Adherence to this date is important to ensure completion of the exercise within the available timeframe. If a response is proposed but the date poses a problem, please advise when it could be submitted.

1468Y

ORGANISATION FOR ECONOMIC
CO-OPERATION AND DEVELOPMENT

NUCLEAR ENERGY AGENCY

SINDOC(86)140

RESTRICTED

Paris, drafted: 6th August 1986

dist: 8th August 1986

English text only

STEERING COMMITTEE FOR NUCLEAR ENERGY

COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

Principal Working Group No. 3: Primary Circuit Integrity

QUESTIONNAIRE

STEAM GENERATOR TUBE PLUGGING CRITERIA

Please return the completed questionnaire by 31st October 1986, to:

Mr. Rick KURTZ
Battelle, Pacific Northwest Laboratory
P.O. Box 999
Richland, WA. 99352
USA

with a copy to:

Dr. N. R. McDONALD
Nuclear Safety Division
OECD Nuclear Energy Agency
38 Blvd. Suchet
75016 Paris
France

Telephone: (1) 45.24.96.79
Telex: 630668 AENNEA
Telefax: (1) 45.24.96.24

Please utilise additional space as required to fully answer questions, attaching extra pages to the back of the questionnaire if necessary.

1469Y

38044

QUESTIONNAIRE
STEAM GENERATOR TUBE PLUGGING CRITERIA

Degraded Pressurized Water Reactor steam generator tubes are removed from service by plugging to avoid breaching primary system integrity. Tube plugging criteria may vary from country to country. The purpose of this study is to determine what tube plugging criteria are being used and what the technical bases are for particular tube plugging criteria. Data from the following questions will be summarized and compared in a report to be issued to CSNI participants.

Tube Plugging Criteria

• 1a What are the current tube plugging criteria for regulation of steam generators? (For example, 40% tube wall loss)

• 1b Are the tube plugging criteria defect specific? (For example, do stress corrosion cracks have different plugging limits in the regulations than pits or wastage?)

• 1c Do the tube plugging criteria depend on defect location in the generator? (For example, are defects in straight tube sections treated differently from defects in the U-bends?)

• 1d Are there examples of tube plugging criteria being used by utilities, that are different from the regulatory requirements? Please state examples. (For example, it is common field practice to plug U-bends with defect indications, regardless of size, since they are assumed to be stress corrosion cracks that may grow through wall in a short time. This differs from the regulatory tube plugging criterion of 40% wall degradation.)

• 1e What are the technical bases for the tube plugging criteria? Please provide references. (For example, current U.S. tube plugging criteria were derived from a model of remaining tube integrity as a function of wall loss for a wastage defect. The tube plugging criteria includes a factor for increased defect enlargement between inspections and another factor for uncertainties associated with the NDE inspection reliability.)

References for the degradation model are:

Empirical data for model derivation is found in:

Inspection for Steam Generator Tube Degradation

• 2a What are the inservice inspection requirements to determine steam generator tube degradation? (Instrumentation, procedures, extent and periodicity requirements)

• 2b What accuracy and precision are associated with the required inservice inspection procedures and instrumentation? In other words, what is the reliability of the NDE method to detect and size defects? What are the bases (experimental/theoretical) for these reliability estimates? Please provide references if available.

• 2c Does the required NDE inspection technique reliably identify the type (eg., cracks, pits, wastage, fretting etc.) of tubing degradation? Is this required? What methodology is used?

• 2d What nondestructive inspection procedures are used in addition to those required? To what extent and how frequently are these alternative techniques employed? What improvement in characterization and sizing of defects do these techniques achieve? (An example would be the use of ultrasonic inspection to size defects following a multifrequency eddy current inspection using a bobbin coil for defect detection)

Steam Generator Tube Repair

• 3a What are the regulatory requirments for the repair and return to service of degraded tubing?

• 3b What are the inspection requirements for repaired tubing?

• 3c What kind of steam generator tubing repair has been used? How extensively (number of tubes/units)? Are there additional repair methods likely to be used in the near future?

• 3d What are the technical bases for plugging of repaired tubes? Have any repaired tubes been removed from service?

Design Basis for Steam Generator Tube Integrity

• 4a What is the basis for the steam generator inspection program and removal of degraded tubing from service? (For example, establishment of a probability for single tube failure of <10E-6 per reactor operating year and a probability for multiple tube failures of <10E-9 per reactor operating year.) Provide documentation/references for establishing this basis.

• 4b Describe empirical/theoretical information and models that have been developed to describe tube rupture, leak rates and inservice inspection reliability.

Comments

Please include any further comments you wish to make including relevant information about tube sleeving and repair and tube testing programmes.

APPENDIX B

EXTENDED INFORMATION FROM U.S. NRC RESPONSE INCLUDES RESPONSES FROM QUESTIONS 1E AND 2B

APPENDIX B

EXTENDED INFORMATION FROM U.S. NRC RESPONSE INCLUDES RESPONSES FROM QUESTIONS 1E AND 2B

Response: Question 1E

Regulatory Guide 1.121, "Bases for Plugging Degraded PWR Steam Generator Tubes," issued for comment in August 1976, defines an acceptable basis for developing steam generator tube plugging criteria which are included in the Technical Specifications of each operating plant. The Regulatory Guide specifies the margins of safety and loading conditions to be considered in establishing the tube plugging criteria. In addition to the factors of safety required on stress, an additional thickness for degrading during operation and ECT error is required to be added to the calculated minimum acceptable tube wall thickness. This approach is intended to ensure that tubes will maintain the minimum acceptable wall thickness until the next inspection and provide margin for the ECT measurement error.

For purposes of illustration, minimum wall requirements calculated for the H. B. Robinson steam generator tubes (Westinghouse Model 44, 0.875 OD X 0.050 THK tubes) in accordance with Regulatory Guide 1.121 are summarized below: Note that this is a partial rather than a complete listing of minimum wall requirements relative to each of the loading cases which must be considered pursuant to Regulatory Guide 1.121, but does include the most limiting cases. In addition, these calculated minimum wall requirements do not include the allowances for additional defect penetration between inspections and eddy current measurement error.

- 26% to ensure no burst under postulated steam line break (SLB).
- 34% to ensure that Code specified margins are maintained for postulated SLB.
- 40% to ensure no yield under normal operating pressure.
- 46% to ensure a margin of 3 to burst with respect to normal operating pressure.
- 42% to ensure that Code specified margins against tube collapse are maintained during LOCA (assumes 2% ovality of tubes).

Before discussing allowances made for eddy current error and expected defect growth between inspections, it is important to note that the above minimum wall requirements are based on very conservative calculations. These calculations generally assume the degradation to involve uniform thinning of the tube walls in the axial and circumferential direction. Actually, operating experience indicates that most flaws tend to involve relatively short axial and/or circumferential dimensions. As illustrated by NRC sponsored burst and collapse testing of artificially defected tubes discussed in NUREG/CR-0718, a flaw of given depth has less and less of a degrading effect on the tube's pressure retaining capability as the axial and/or circumferential dimensions

of the flaw become smaller and smaller. Indeed, many flaws such as small pits or short cracks can go entirely through wall causing a small leak before the pressure retaining capability of the tube has degraded sufficiently to render the tube susceptible to rupture under normal, transient or postulated accident conditions. Westinghouse test data indicate that 100% through wall axial cracks will cause a primary to secondary leakage rate in excess of 500 gallons per day under normal operating pressure differentials before the crack becomes of sufficient axial length to render the tube susceptible to rupture under more severe pressure loadings associated with postulated accidents.

Another important element of conservatism inherent in the calculated minimum wall requirements are the assumed material properties (e.g., yield and ultimate strength). Plugging limit calculations are typically based on Code minimum material properties. In the case of H. B. Robinson, material property data was available for the heats of material from which the steam generator tubes were fabricated. This data was utilized to calculate lower statistical tolerance limits for yield and ultimate strength such that there is 95% confidence that 95% of the tube population will have greater strength.

Based on the limiting minimum wall requirement above for H. B. Robinson (i.e., 46% based on a margin of 3 with respect to normal operating pressure), a plugging limit of 40% provides only a 14% allowance to account for eddy current measurement error and additional defect growth between inspections. However, operating experience and laboratory data indicate that actual eddy current measurement errors in conjunction with additional defect growth between inspections sometimes will exceed this allowance. Early NRC sponsored studies regarding potential ECT measurement errors were performed as part of Phase I of the Steam Generator Tube Integrity Program as documented in NUREG/CR-0718. These studies were performed with tube specimens with machined defects to simulate wastage and crack type flaws. Figures B.1, B.2, and B.3 indicate how ECT depth measurements compared with the actual depth. As seen in Figure B.1 for tube specimens containing EDM slots (i.e., electro-discharged machined slots to simulate linear crack type flaws), measurement errors in the non-conservative direction ranged to as much as 40 to 50%. The subject tube specimens were subsequently subjected to burst testing. Figure B.4 correlates the burst test strength of each tube specimen with the eddy current depth indication for that tube, regardless of the actual geometry of the defect. It should be noted that burst pressures in excess of 4000 psi indicate a margin of at least three with respect to normal operating pressure which as discussed earlier, is the most limiting criteria for establishing the minimum wall requirement for Westinghouse Model 44 steam generator tubes. It can be seen from the Figure that all tube specimens exhibiting a burst strength of less than 4000 psi also exhibited an eddy current indication of at least 60% and thus would have been considered defective tubes requiring plugging. However, many of the tube specimens exhibiting ECT indications exceeding 60% exhibited burst strengths exceeding 4000 psi. Part of the reason for this is that the specimens included simulated flaws of varying length as well as varying depth. As previously discussed, defect length is an important parameter affecting the burst strength of tubes.

Combustion Engineering has generated its own laboratory data shown in Figure B.5 which appears to be quite consistent with the data and trends in Figure B.4.

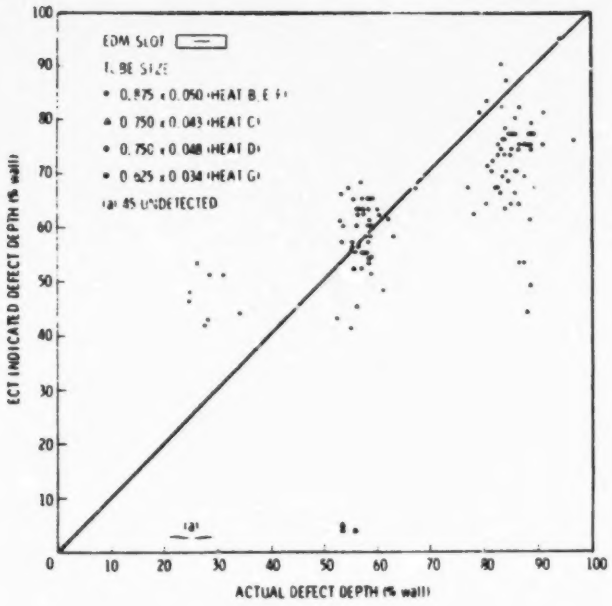

EDM SLOT
TUBE SIZE
• 0.875 x 0.050 (HEAT B, E, F)
▲ 0.750 x 0.043 (HEAT C)
• 0.750 x 0.048 (HEAT D)
• 0.625 x 0.034 (HEAT G)
(a) 85 UNDETECTED
ECT INDICATED DEFECT DEPTH (% wall)
ACTUAL DEFECT DEPTH (% wall)

FIGURE B.1. Eddy Current Indicated Defect Depth Versus Actual Depth for EDM Slot Specimens

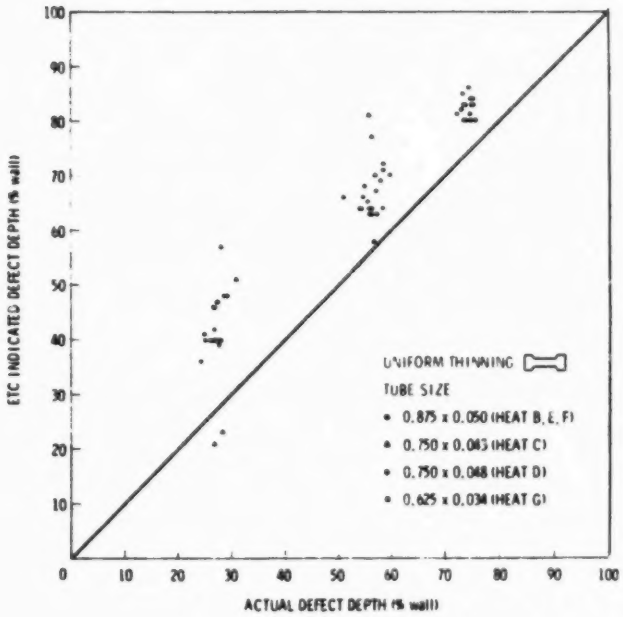

UNIFORM THINNING
TUBE SIZE
• 0.875 x 0.050 (HEAT B, E, F)
▲ 0.750 x 0.043 (HEAT C)
• 0.750 x 0.048 (HEAT D)
• 0.625 x 0.034 (HEAT G)
ETC INDICATED DEFECT DEPTH (% wall)
ACTUAL DEFECT DEPTH (% wall)

FIGURE B.2. Eddy Current Indicated Defect Depth Versus Actual Depth for Uniform Thinning Specimens

BEST COPY AVAILABLE

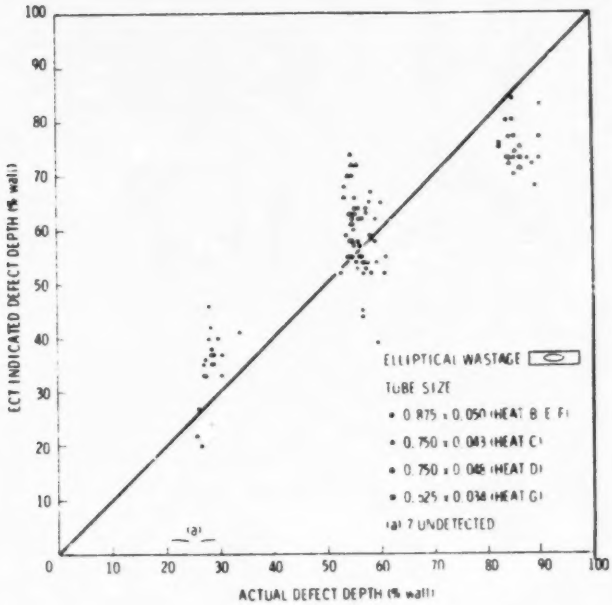


FIGURE B.3. Eddy Current Indicated Depth Versus Actual Depth for Elliptical Wastage Specimens

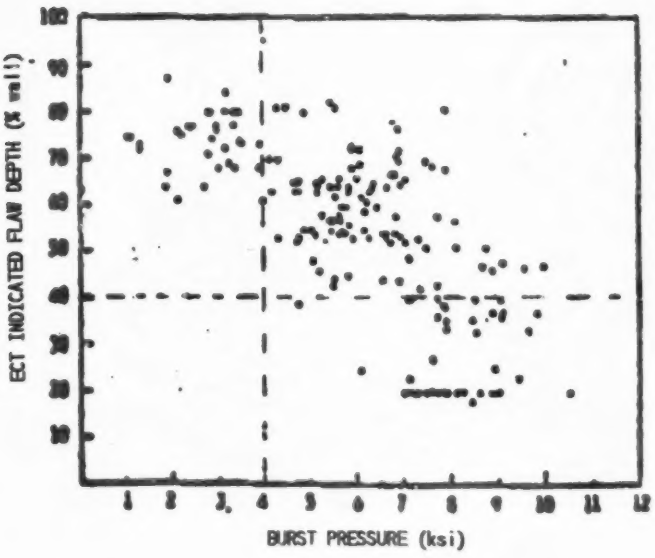
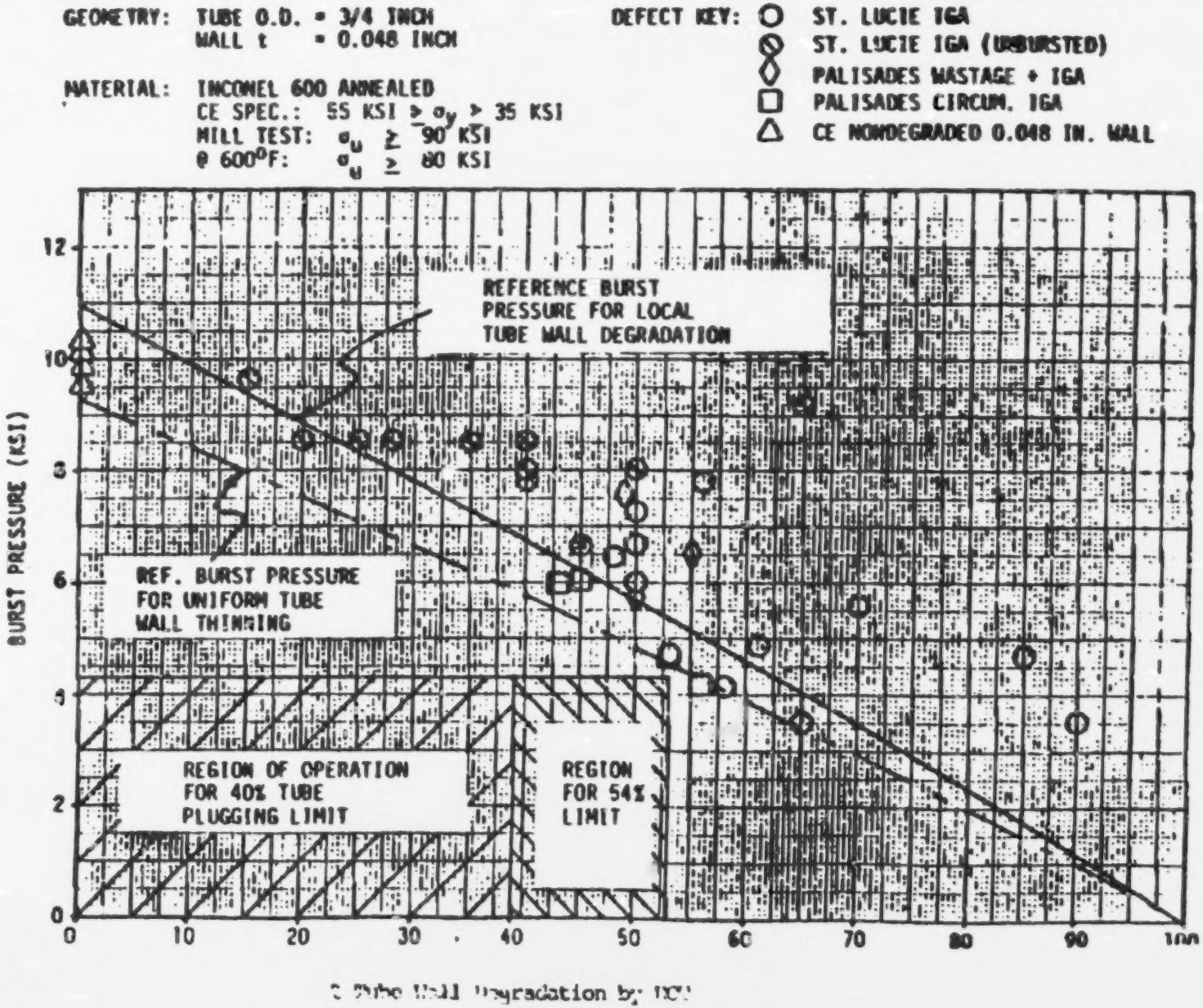


FIGURE B.4. Depth Indications of Eddy Current Tests Versus Burst Pressure for All Tube Geometrics

BEST COPY AVAILABLE



% Tube Wall Degradation by IGA

FIGURE B.5. IGA Tube Burst Test Data - Laboratory Defects

BEST COPY AVAILABLE

A tentative conclusion to be drawn from Figures B.4 and B.5 is that existing plugging limits (typically 40%) are adequate to ensure tube integrity provided that degradation rates between inspections are not excessive. This appears to be true primarily because conservatisms implicit in the calculated minimum wall requirements more than compensate for potential non-conservatisms concerning the allowance for eddy current error.

Followup studies by the NRC staff are being performed to validate the above conclusions with data from more realistic laboratory degradation specimens and from tube specimens obtained from the field. These studies are being performed as part of the Steam Generator Group Project which includes work performed as part of Phase II of the Steam Generator Tube Integrity Program. As part of these studies, a round robin ECT test on laboratory produced intergranular stress corrosion cracked (IGSCC) tube specimens was performed by a number of qualified inspection teams using a variety of different techniques and equipment. The results of this study indicated that average crack depths may be underestimated by as much as 10 to 40% depending on the techniques, equipment, and personnel employed. Similarly, large measurement errors have been obtained during another round robin test conducted on tube specimens removed from the Surry steam generator in Hanford, Washington, which contained wastage and/or pitting type flaws. Ultimately, the tube specimens employed in these round robin tests will be subjected to burst tests to correlate burst strengths with ECT readings similar to what have been done in Figures B.4 and B.5.

The PWR Steam Generator Eddy Current Inspection Guidelines published by EPRI provide a very comprehensive description and assessment of eddy current test technology, including detection capabilities and potential measurement errors for various types of degradation, and guidelines for enhancing eddy current detection and measurement accuracy for specific applications.

Response: Question 2B

NPC data concerning ECT reliability, and references for this data, were discussed earlier in response to question 1E.

Accuracy and precision requirements are specified in the ASME Code, Section V, Article 8 - Appendix 1 (Summer 1983 edition). These requirements incorporate a calibration standard consisting of a tube with round, flat bottom holes of different depths. As noted by EPRI, however, in the EPRI ECT inspection guidelines, the ASME calibration standard is designed to verify consistent eddy current system response. It does not establish optimum working sensitivity in all cases nor does it provide for the best estimation of the depth of tube wall discontinuities under all circumstances. Use of the ASME standard in estimating flaw depth may result in conservative or nonconversative estimates depending on characteristics of the particular flaw. For this reason, the EPRI ECT inspection guidelines endorse paragraph C.2.3E of Regulatory Guide 1.83 which reads as follows:

> "Standards consisting of similar as-manufactured steam generator tubing with known imperfections should be used to establish sensitivity and to calibrate the equipment. Where practical, these standards should include reference flaws that simulate the length,

depth, and shape of actual imperfections that are characteristic of past experience."

The reliability of ECT to detect and size defects is a strong function of the geometry, orientation, and volume of the defect; the defect's location relative to extraneous sources of noise (affecting signal to noise ratio); the type of eddy current equipment employed (e.g., data analysis equipment, test probes, etc.); and the training, experience, and alertness of the data evaluators. Reliable detection and sizing of defects cannot be assured for all defect types for all possible test conditions and equipment. New damage mechanisms may be encountered during in-service inspection which are not reliably detected or sized because of non-optimal inspection procedures for the specific flaw type, location, and orientation. In these situations, alternative inspection procedures and equipment will need to be employed to ensure a reliable inspection. The EPRI inspection guidelines provide a detailed discussion of capability of various eddy current test procedures and equipments to reliably detect and size various types of flaws. These discussions include a detailed review of available experimental and field data.

It is important to note that adherence to minimum requirements as specified in the ASME Code does not ensure that ECT inspection programs will reliably detect and accurately size many of the kinds of defects occurring today. The NRC staff relies on the utility's being aware of the limitations of various eddy current test techniques and being alert for signs that alternative, more sensitive techniques should be employed. Apart from safety considerations, utilities have a strong economic incentive to employ ECT techniques as appropriate to ensure the reliable detection and sizing of flaws. EPRI has issued its PWR Steam Generator Inspection Guidelines which provide excellent guidance to utilities for performing effective and reliable inspection programs. Multi-frequency ECT techniques (not required by NRC) are virtually in universal use by U.S. utilities. Many utilities are utilizing state-of-the-art digital data acquisition and analysis systems (e.g., Zetec's MIZ-18 system) which provide a significant increase in dynamic range and signal to noise ratio over analog systems. Specialized eddy current probes such as various types of surface riding pancake probes are in frequent use when dealing with the detection and sizing of IGSCC and IGA flaws.

APPENDIX C

CANADIAN REGULATORY CRITERIA
(APPENDED TO QUESTIONNAIRE RESPONSE)

12.7 Records

Inspection records and the issuance of reports shall comply with the requirements of Clause 11.

13. Fuel Channel Feeder Pipes—Supplementary Inspection

13.1 Scope

Clause 13 establishes the requirements for the supplementary periodic inspection of fuel channel feeder pipes.

13.2 Inaugural Inspection

(a) A visual inaugural inspection of all feeder pipes and all supports shall be performed on preoperational reactor units and a record made of any observations arising from the inspection relating to the pressure-retaining integrity of these components; and

(b) wall thickness measurements on a minimum of 20 feeder pipes shall be performed on all pre-operational reactor units. The inspection areas shall be chosen from those which are accessible and which are likely to experience the greatest reduction in wall thickness.

13.3 Periodic Inspection

13.3.1 Inspections

(a) A general visual inspection of feeder piping, piping supports and fret sleeves shall be carried out. Disassembly of supports or fret sleeves is not required. The use of remote inspection equipment is permitted; and

(b) wall thickness measurements shall be performed on feeder pipes as required below.

13.3.2 Single Unit Stations

A minimum of 10 feeder pipes selected from the inaugural inspection sample shall be subjected to periodic inspection.

13.3.3 Multi-unit Stations

For periodic inspection of multi-unit stations, the inspection sample size on the designated first unit in service shall be as required in Clause 13.3.2 above. For subsequent units, the inspection sample size shall be no less than the following:

(a) designated second unit in service: 7 feeders;

(b) designated third unit in service: 4 feeders; and

(c) designated fourth unit in service: 3 feeders.

13.3.4 Inspection Interval

The scheduling of inspections shall comply with the requirements of Clause 7.6.

13.4 Inspection Methods and Procedures

The inspection methods and procedures shall comply with the requirements of Clauses 4.1 and 4.2.

13.5 Inspection Staff

The requirements given in Clause 5 shall apply.

13.6 Evaluation of Results and Disposition

13.6.1

The evaluation and disposition shall comply with Clause 8, except that acceptance and recording criteria shall comply with Clause 13.6.2.

13.6.2 Acceptance and Recording Criteria

(a) Indications of reduction from the initial feeder pipe wall thickness of 20% or greater shall be recorded and reported;

(b) indications of reduction from the initial feeder pipe wall thickness of 40% or greater shall be submitted to the authority for disposition; and

(c) for visual inspection, the provisions of Clause 8.2.1.2 shall apply.

13.7 Records

Inspection records and the issuance of reports shall comply with the requirements of Clause 11.

14. Steam Generator Tubes—Supplementary Inspection

14.1 Scope

Clause 14 establishes the requirements for the supplementary periodic inspection of steam generator tubes.

14.2 Inaugural Inspection

(a) A minimum of 1.5% of the total number of tubes in one steam generator in each reactor unit shall be subject to inaugural inspection;

(b) tubes to be inspected shall be chosen to include those which are considered to be subject to the most severe service. The effects of the various service conditions, both individually and collectively, shall be considered in selecting the inspection sample; and

(c) to the extent practicable, the full length of each selected tube shall be inspected.

14.3 Periodic Inspection

(a) The number of tubes to be inspected in a reactor unit shall be not less than 1% of the total number of tubes in one steam generator;

(b) to the extent practicable, the full length of each selected tube shall be inspected;

(c) each leaking tube shall be located and all tubes whose centrelines are located within a radius of 2.5 times the tube spacing from the centreline of the leaking tube shall be inspected;
(d) each sample of tubes selected for periodic inspection shall include those tubes having the most significant recordable discontinuities and tubes in those areas where operating experience has indicated the likelihood of deterioration; and
(e) the scheduling of inspections shall comply with the requirements of Clause 7.6.

14.4 Inspection Methods and Procedures

14.4.1 Methods
Eddy current or equivalent inspection methods shall be used and shall comply with the requirements of Clause 4.1.

14.4.2 Procedures
Procedures shall comply with the requirements of Clause 4.2.

14.4.3 Reference Specimen
(a) A reference specimen shall be made to include the following discontinuities:
(i) external circumferential groove;
(ii) internal circumferential groove;
(iii) through-wall hole of 0.060 in (1.5 mm) diameter, and
(iv) external wall reduction of 20% of tubing wall thickness,
(b) the external and internal grooves shall be 0.125 in (3 mm) wide and flat bottomed and shall have a depth equal to 20% of the nominal wall thickness; and
(c) in all other respects, the reference specimen shall be identical to the steam generator tubing in the as-new condition.

14.5 Inspection Staff
The requirements given in Clause 5 shall apply.

14.6 Evaluation of Results and Disposition

14.6.1
The evaluation and disposition shall comply with Clause 8, except that acceptance and recording criteria shall comply with Clause 14.6.2.

14.6.2 Acceptance and Recording Criteria
(a) Indications of 20% or greater depth of tubing wall thickness shall be recorded and reported; and
(b) indications where the anticipated wall loss would exceed 40% of nominal wall thickness prior to the next inspection shall be submitted to the authority for disposition.

14.7 Records
Inspection records and the issuance of reports shall comply with the requirements of Clause 11.

APPENDIX D

FRENCH GUIDELINES FOR IN-SERVICE INSPECTION OF STEAM GENERATOR TUBING (APPENDED TO QUESTIONNAIRE RESPONSE)

APPENDIX D

FRENCH GUIDELINES FOR INSERVICE INSPECTION OF STEAM GENERATOR TUBING

(C. BIRAC / CEA)

1. FOREWORD

The general practice is, beyond the starting of the installation, to be able to evince, throughout its industrial operation, any alterations detrimental to the nuclear plant safety : this is the purpose filled by inservice inspection.

The objectives common to the equipment of the primary system are specified in a statutory text under the Order of February 26, 1974.

Since the objectives are specified, the method to achieve them is established for each equipment in turn, within the scope of preventive maintenance programmes drawn up by the plant operator and approved by the Safety Authorities. The operator also defines the procedures describing the inspection methods and stating the related notation thresholds.

BEST COPY AVAILABLE

2. THE REGULATIONS

Regulations are, on the whole, considered with two different approaches :

- a directing approach consisting in listing the equipment to be monitored, stating the appropriate method and periodicity of the checks.

- a broader and more flexible approach, defining the objectives to be achieved but leaving the operator scope for the means to reach such objectives.

This approach may appear less stringent, but this is a false appearance because it actually compels the operator to assume his responsibilities ; moreover, it is much more flexible to cope with new problems encountered and progress in non-destructive examination methods.

This is the latter approach which comes under the Order of February 26, 1974, enforcing the general regulations relating to pressure vessels to the principal primary system of pressurized water reactors.

The Order governs the design phases as well and the construction and inservice inspection.

As regards inservice inspection, the two following major concepts are introduced :

- the surveillance of defects development : "the user provides the facilities required to detect the development of defects in the vessel revealed both at the end of construction and during service",

- the necessity of carrying out a complete preservice inspection in order to have a reference for the indications detected,

- the necessity of continuous surveillance and periodic inspections (periods less than 2 years) and of complete inspections (periods less than ten years, except for the first complete inspection which shall take place thirty months at the most after the initial fuel loading).

These general regulations applicable to the objectives are backed up, as far as the steam generating equipment is concerned, with a preventive maintenance programme defining the sampling rate and the procedures defining the examination conditions.

These specifications can evolve more easily than an Order and thus allow for the experience gained and the development of methods.

3. PREVENTIVE MAINTENANCE PROGRAMME AND INSPECTION PROCEDURES

It should be first pointed out that although the method described applies to the different deterioration processes found in power plant installations, its presentation mainly concerns a predominant failure, i.e. I.G.S.C.C. (intergranular stress corrosion cracking) on the inner skin of the transition rolling zones.

The preventive maintenance programme, drawn up by the plant operator, defines a standard eddy current method based on the following general principles :

- all the tubes are examined prior to starting on initial preservice inspection. The inspection on subsequent shutdowns is carried out by sampling.

- tubes are examined throughout their length.

- sampling is performed on different tubes at each shutdown.

- the sampling rate applicable to one or several steam generators of a power plant during a given shutdown period depends on :

. the type of indications detected during the shutdown

. the number of indications detected during the preceding shutdown.

The decisions made at the end of the standard eddy current method (leaving as it stands, expert investigation by additional examination, expert investigation by tube extraction, plugging) are dependent upon the characteristics of the indications detected (especially the position of the indication in the tube, length of wall loss).

The estimated depth of the defects is therefore not the only criterion taken into account in the decision. In particular, as regards the straight portion of the tubes, the plugging criterion is 40 % of the tube thickness, while a length criterion (16 mm) is used for transition rolling zones.

As regards the non-destructive examination of the tube bundle, two eddy current methods are used essentially, namely :

- **a standard method**

This is an eddy current multifrequency method, using a probe operating in the absolute and differential mode. This method, which has been developed industrially since 1975 has a two-fold purpose :

. detection of defects produced by fabrication, on preservice inspection or detected in service on periodic inspections.

. geometric characterization of rolling transition zones, since certain geometries may contribute to induce faults.

Multiple studies carried out on artificial and real defects have led to :

. the definition of the detection and characterization capacities of the probe,

. the establishment of a strict and detailed examination procedure (several notation thresholds according to the position of the indication and the characteristics obtained by the eddy current method) ensuring a good reproducibility of the analysis.

However, and this is a highly important point, in addition to the multiple above-mentioned studies, it is necessary to validate the results of the examinations using the eddy current method by proceeding to tube extraction in order to improve the knowledge of :

- the inservice development of the deterioration process, by means of fine metallurgical expert investigations,

- the detrimental effect of the defects, notably by bursting tests,

- the detection and characterization capacité of the non-destructive examination methods as well as the adequacy of the procedures used.

- <u>an expert investigation method</u>

It was for reasons similar to those mentioned above that a new eddy current probe was developed. Although the standard probe was suitable for detecting the I.G.S.C.C. in the transition rolling zones, it was inoperative for characterizing the cracks, i.e. for giving their orientation (longitudinal and transverse) and evaluating their length.

Depending on the parameters supplied by the new probe, a decision will be made to leave the tube as it stands, to extract it or to plug it.

After having defined the role of the probe, some of its operating features should be mentioned. It is also a multifrequency probe operating in the differential and absolute mode ; in addition, it is a rotating probe moving along a helical path in the tube ; the control range is limited to the rolling transition zones.

The results obtained with this probe agree with the lengths of the defects measured on tubes subjected to expert investigation.

4. CONCLUSION

Following a review of the principles governing French regulations as regards inservice inspection, we have shown that although it is ambitious on the objectives, it gives the plant operator great liberty in the choice of the means to achieve them.

The operator has adapted his examination method, maintenance programme and inspection procedures to cope with the type of deteriorations found in the power plant installations. Tube extractions allow definition of detection and characterization capacities of the standard inspection method and expert investigation method and they also enable the definition of examination procedures to be improved.

This fairly flexible statutory approach has promoted, in highly standardized power plant installations, the acquisition of experience feedback and assimilation of progress made in inspection methods.

DISTRIBUTION

No. of Copies

OFFSITE

10 Dr. Joseph Muscara
Materials Engineering Branch
Div. of Engineering Safety
Nuclear Regulatory Commission
Mail Stop NL/S-217C
Washington, DC 20555

Dr. C. Y. Cheng
Office of Nuclear Reactor Regulation
Nuclear Regulatory Commission
Washington, DC 20555

Mr. C. McCracken
Office of Nuclear Reactor Regulation
Nuclear Regulatory Commission
Washington, DC 20555

Mr. H. Conrad
Office of Nuclear Reactor Regulation
Nuclear Regulatory Commission
Washington, DC 20555

Mr. E. Murphy
Office of Nuclear Reactor Regulation
Nuclear Regulatory Commission
Washington, DC 20555

Mr. K. Wickman
Office of Nuclear Reactor Regulation
Nuclear Regulatory Commission
Washington, DC 20555

No. of Copies

4 Mr. C. S. Welty
Electric Power Research Institute
3412 Hillview Avenue
P. O. Box 10412
Palo Alto, CA 94303

5 Mr. H. S. McKay
Virginia Electric Power Co.
P. O. Box 26666
Richmond, VA 23261

3 Dr. R. A. Clark
Photon Sciences
11816 N. Creek Pkwy.
Bothell, WA 98011-8012

Mr. M. Anderson
Northern States Power
414 Nicolett Mall
Minneapolis, MN 55401

Mr. A. E. Curtis, III
Rochester Gas & Electric Corp.
89 East Avenue
Rochester, NY 14649

Ms. D. Currier
Florida Power & Light
9250 W. Flagler
Miami, FL 33120

Mr. D. Halama
New York Power Authority
123 Main Street
White Plains, NY 10601

Mr. J. Haning, DMT-6C
Houston Lighting & Power Co.
P. O. Box 1700
Houston, TX 77001

No. of Copies

Mr. C. W. Hendrix, Jr.
Duke Power Company
Nuclear Production Dept.
P. O. Box 33189
Charlotte, NC 28242

Mr. K. Hoffman
Baltimore Gas & Electric Co.
Calvert Cliffs Nuclear Power Plant
Lusby, MD 20657

Mr. J. Kang
Pacific Gas & Electric Co.
Dept. of Eng. Research
3400 Crow Canyon Road
San Ramon, CA 94583

Mr. A. Matheny
Southern California Edison
P. O. Box 128
San Clemente, CA 92672

Mr. G. Severance
Consumers Power Co.
1945 W. Parnall Road
Jackson, MI 49201

Mr. J. Benson, Assoc. Eng.
Northeast Utilities
P. O. Box 270
Hartford, CT 06101

Mr. T. Fauble, Engineer
SMUD/Rancho Seco
14440 Twin Cities Road
Herald, CA 95638

Mr. D. L. Sessler
Tennessee Valley Authority
1735 Chestnut St. Towers II
Chattanooga, TN 37401

Mr. D. L. Smith
Virginia Electric & Power Co.
P. O. Box 26666
1 James River Plaza
Richmond, VA 23261

No. of Copies

Dr. Costis Spalaris
Quadrex Corporation
1700 Dell Avenue
Campbell, CA 95008

Mr. Thomas Beeman
London Nuclear Services, Inc.
2 Buffalo Avenue
Niagara Falls, NY 14303

Mr. Ernest Hayden
Westinghouse Electric Corp.
Steam Generator Services

Foreign

4 Dr. J. L. Campan
Department Manager
Water Reactor Service
C.E.A./Cadarache B.P. No 1
13115 Saint Paul Lez Durance
Cadarache, FRANCE

Mr. C. Birac
DAS/STAS/SAM
Commissariat a l'Energie Atomique
CEN/FAR
B.P. No. 6
92265 Fontenay-aux-Roses
FRANCE

4 Mr. M. Oishi, Director
Steam Generator Project NUPEC
Shuwa Kamiya-Cho Bldg.
3-13, 4-Chome, Toranomon,
Minato-Ku, Tokyo 105
JAPAN

4 Dr. R. DeSantis
R&D Manager
Ansaldo DBGV
Viale Sarca 336
Milano, ITALY 20125

200 Dr. N. R. McDonald
OECD-Nuclear Energy Agency
38 Blvd. Suchet
75016 Paris, FRANCE

No. of
Copies

Mr. Malcolm Russell
NDE Applications
CEGB
Bridgewater Road
Bedminster Down
Bristol, ENGLAND

Mr. John Tomlinson
Central Electrity Generating
Board
NDT Applications Centre
Manchester, U.K. M239LL

ONSITE

50 Pacific Northwest Laboratory

R. J. Kurtz (43)
Publishing Coordination (2)
Technical Report Files (5)

NRC FORM 335 (2.84) NRCM 1102, 3201, 3202

U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

SEE INSTRUCTIONS ON THE REVERSE

1 REPORT NUMBER (Assigned by TIDC, add Vol. No., if any)
NUREG/CR-5016
PNL-6341
CSNI No. 140

2 TITLE AND SUBTITLE
Compendium and Comparison of International Practice for Plugging, Repair and Inspection of Steam Generator Tubing

3 LEAVE BLANK

4 DATE REPORT COMPLETED
MONTH: October YEAR: 1987

5 AUTHOR(S)
R. A. Clark and R. J. Kurtz

6 DATE REPORT ISSUED
MONTH: April YEAR: 1988

7 PERFORMING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code)
Pacific Northwest Laboratory
P. O. Box 999
Richland, Washington 99352

8 PROJECT/TASK/WORK UNIT NUMBER

9 FIN OR GRANT NUMBER
B2097

10 SPONSORING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code)
Division of Engineering
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Comm.
Washington, DC 20555

Organization for Economic Co-operation and Development
Nuclear Energy Agency

11a TYPE OF REPORT
Technical

b PERIOD COVERED (Inclusive dates)

12 SUPPLEMENTARY NOTES

13 ABSTRACT (200 words or less)

The Committee on the Safety of Nuclear Installations (CSNI) of the Organization for Economic Cooperation and Development - Nuclear Energy Agency (OECD-NEA) is an international body of scientists and engineers with responsibilities for nuclear safety research and nuclear licensing. The CSNI fosters international cooperation in nuclear safety amongst OECD member countries. In July 1986, the Committee's Principal Working Group on Primary Circuit Integrity agreed it would be useful to those setting criteria and making decisions about plugging of degraded steam generator tubes to have a better appreciation of the criteria presently employed in other members countries and their technical bases. The United States Nuclear Regulatory Commission (U.S. NRC) offered to arrange the preparation of a comparative summary for CSNI based on responses to a questionnaire circulated by the OECD-NEA among member countries. The following report is based upon the information obtained from nine countries currently operating pressurized water reactors (PWRs).

14 DOCUMENT ANALYSIS - a KEYWORDS/DESCRIPTORS
Steam Generator

b IDENTIFIERS/OPEN-ENDED TERMS

15 AVAILABILITY STATEMENT
Unlimited

16 SECURITY CLASSIFICATION
(This page) Unclassified
(This report) Unclassified

17 NUMBER OF PAGES

18 PRICE

*U.S. GOVERNMENT PRINTING OFFICE: 1988-202-292:80048

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE, $300

SPECIAL FOURTH CLASS RATE
POSTAGE & FEES PAID
USNRC
PERMIT No. G-67